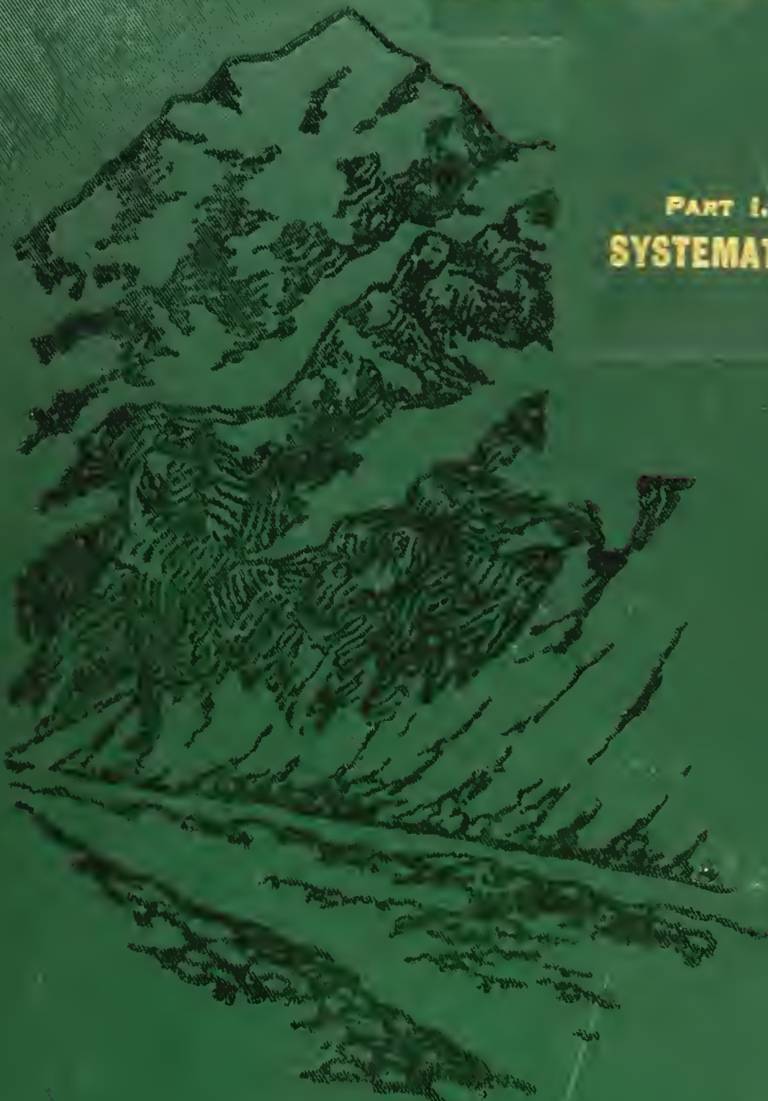
GEOMORPHOLOGY

OF

NEW ZEALAND.

PART I.

SYSTEMATIC.



F. G. Radcliffe, photo.

Milford Sound, N.Z.: A Typical Fiord.

NEW ZEALAND BOARD OF SCIENCE AND ART.

Manual No 3.

GEOMORPHOLOGY OF NEW ZEALAND.

PART I.—SYSTEMATIC.

An Introduction to the Study of Land-forms.

BY

C. A. COTTON, D.Sc., F.N.Z.Inst., F.G.S.,

Professor of Geology, Victoria University College, Wellington.

WELLINGTON, N.Z.:

DOMINION MUSEUM.

1922.

The hills are shadows, and they flow
  From form to form, and nothing stands;
  They melt like mist, the solid lands,
Like clouds they shape themselves and go.

—TENNYSON: "In Memoriam"

PREFACE.

Geomorphology has become in recent years a well-developed science based on firmly established principles. If the assumption can be made that the reader is familiar with the fundamental principles of the science, intelligible explanatory description of a landscape becomes possible. In the hope of setting forth these principles in a convincing manner, and thus popularizing in New Zealand the fascinating study of land-forms, the present work (Part I) is cast in the form of a text-book of geomorphology for New Zealand students and general readers.

The systematic treatment of the subject has been adopted in the hope that it will prepare readers not only to follow the explanatory descriptions of land-forms in a regional treatment of the surface of New Zealand, now in preparation for publication as Part II of *Geomorphology of New Zealand,* and to appreciate geomorphological articles in scientific journals, but also to undertake for themselves with some degree of confidence the interpretation of the landscapes they see about them. Included in Part I are brief descriptions, in most cases accompanied by illustrations, of a large number of examples of typical land-forms chosen from New Zealand localities—in many cases well-known scenic resorts, as well as places within easy reach of the cities.

A text-book such as this is necessarily in great part a compilation, and is made possible only by the labours of many workers in a wide field. I have attempted to acknowledge my indebtedness to these many workers by a few references to original publications; but in a book for the general reader it is not desirable that references to literature should be over-numerous, and such acknowledgments as appear in the text by no means indicate the full extent to which the work of others has been drawn upon. I take this opportunity, therefore, of

acknowledging my debt to all the pioneers in geomorphology, and most of all to that great teacher Professor W. M. Davis, of Harvard University.

I wish also to express my thanks to all those who have placed at my disposal illustrative material—especially to Professor W. M. Davis for his generous permission to make free use of his block diagrams (in particular, figs. 331 and 332); to Mr. F. G. Radcliffe, Whangarei, for permission to reproduce a large number of his New Zealand photographs; to Messrs. G. Rose, Melbourne, and D. J. Aldersley, Lower Hutt, for permission to reproduce several photographs; to Dr. P. Marshall for permission to use illustrations from his *Geology of New Zealand*; to Dr. L. Cockayne for permission to take prints from many photographic negatives; to Mr. R. W. Holmes, I.S.O., late Engineer-in-Chief, Public Works Department, Professor W. N. Benson, and Mr. J. A. Bartrum for a number of photographs obtained through their good offices; to Professors R. Speight, J. Park, and Herbert E. Gregory, Dr. P. Marshall, Dr. J. Allan Thomson, Messrs. A. C. Gifford, W. A. McKay, B. C. Aston, G. L. Adkin, W. D. Reid, L. I. Grange, T. L. Lancaster, S. Taylor, J. Wood, the New Zealand Geological Survey, and the New Zealand Tourist Department for various photographs. (Wherever possible the name of the photographer has been placed below each photographic illustration.) I am indebted also for the use of process blocks to the American Geographical Society, the proprietor of the *American Journal of Science*, the New Zealand Institute, the New Zealand Geological Survey, the New Zealand Tourist Department, and the editors of the *Geological Magazine*, the *Journal of Geology*, and the *New Zealand Journal of Science and Technology*.

Wellington, June, 1922. C. A. COTTON.

CONTENTS.

CHAPTER VI.

CHAPTER VII.

CHAPTER VIII.

CHAPTER IX.

CHAPTER X.

CHAPTER XI.

CHAPTER XII.

CHAPTER XIII.

CHAPTER XIV.

CHAPTER XV.

CHAPTER XVI.

CHAPTER XVII.

CHAPTER XVIII.

CHAPTER XIX.

CHAPTER XX.

GEOMORPHOLOGY OF NEW ZEALAND.

PART I.—SYSTEMATIC.

CHAPTER I.

INTRODUCTION.

The science of geomorphology. The relation of geomorphology to geology and to geography. Empirical *versus* explanatory description of land-forms. Empirical nomenclature. Literature of geomorphology.

The Science of Geomorphology.—Geomorphology as a science had its beginning very early in the nineteenth century, when John Playfair demonstrated, in his *Illustrations of the Huttonian Theory of the Earth* (1802), that valleys are the work of the streams that flow in them. This recognition of the prime importance of erosion in the development of the forms of the earth's surface arose out of Playfair's acceptance of James Hutton's geological principle of uniformitarianism, championed at a much later date by Charles Lyell—the principle that the origin of the surface forms, as well as of the rocks, is to be ascribed not to sudden catastrophic or miraculous events, but to the action of forces still in operation.

By the middle of the century the ability of waves of the sea to wear away the margin of the land was fully realized, and A. C. Ramsay explained clearly how plains might thus be formed. The importance of the results of this process on the land-surface were indeed for a time overestimated in England, and it was

not until 1867 that William Whitaker there re-established the efficiency of subaerial denudation to account for the origin of valleys (81).*

About the same time several scientific exploratory surveys in the west-central region of the North American continent were bringing to light examples on a grand scale of the erosive action of rivers and of subaerial agents in general. There J. W. Powell developed the principle that not only does subaerial erosion sculpture a land-mass, but that it is capable also, sufficient time being allowed, of destroying again the relief thus etched out, and wearing the surface down until it is nowhere far above the level of the sea. G. K. Gilbert, also, in his *Geology of the Henry Mountains* (1877), lucidly and at considerable length worked out the fundamental principles of land-sculpture.

These and other pioneers in North America were followed in the later decades of the nineteenth century by an enthusiastic band of workers on the morphology of the land. Chief among these, W. M. Davis, who was impressed with the value of Powell's principle of "base-levelling," assisted in crystallizing the conception by inventing the now well-known term "peneplain" for the resulting almost featureless lowland. He has introduced also the idea of the cycle of erosion—or, as he prefers to call it, the "geographical cycle"—a most useful concept in the systematization of the subject and the description of land-forms; and by long-continued efforts he has done much to establish the position of geomorphology among the sciences.

In Europe meanwhile much was being done in the way of systematization and classification of land-forms, particularly by F. von Richthofen and Albrecht Penck. Penck and others have devoted much attention also to the sculpture of mountains by glaciers; and our knowledge of the work of wind in arid deserts is largely due to the careful studies of Johannes Walther and S. Passarge.

The Relation of Geomorphology to Geology and to Geography.—To the geologist the form of the surface is a subject of interest because land-forms are produced by the interaction of the various geological processes which he must study in order to understand

* See Appendix: Reading References.

the mode of production and the transportation and deposition of rock-forming materials. It has for him, however, a further interest in that it preserves a record—in many areas the only record preserved—of a period of earth-history, and, seeing that for the world as a whole the sedimentary record of the post-Tertiary periods is extremely scanty, it is necessary that he should be alive to the importance of the erosional record.

There have been in the remote past, moreover, periods of wide-spread erosion, which are marked by the great unconformities in the geological column. Each surface of unconformity is an ancient eroded surface, and, like the eroded surface of the modern lands, it preserves a record—unfortunately not a complete record, however—of the period of erosion. Much may be learned of geological history by the study of unconformities, a prerequisite for which is a knowledge of the principles of geomorphology as developed from the study of existing land-forms.

To the geographer, on the other hand, the surface of the earth is of importance as the field of activity of organized beings, and notably as the abode of man. He has searched, and is searching, for a method of describing its relief.

Empirical versus Explanatory Description of Land-forms.— Two methods suggest themselves for the description of relief—the empirical and the explanatory. A few geographers favour the former, more the latter. The empirical method is employed in everyday speech: there are, for example, the empirical terms *hill*, *ridge*, *spur*, *valley*, *lake*, &c.; and some empirical terms cannot be excluded from the most technical explanatory description. An exhaustive description of a region in purely empirical terms would, however, make very dull reading. To convey a clear impression— if, indeed, it is capable of conveying a clear impression—an empirical description must be made in great detail. No individual element of the surface must be allowed to escape notice. While in a description made for a purely geographical purpose many empirical terms may perhaps be profitably employed, it becomes necessary (to hold the reader's attention, if for no other purpose) to introduce the explanatory element—to explain the origin, that is to say, of the landscape-features to which attention is directed.

A full explanatory description employing the analytical method and perhaps treating the features under discussion as though they

were the first of the kind that had ever been described may, however, run to a great length—a length that is altogether disproportionate to the writer's estimate of the value in a geographical work of a description of the relief. So there is required some method of condensed explanatory description which will ensure brevity and at the same time indicate that the features of a particular area are not unique, but belong to certain classes of forms previously known. This necessity has been largely met by the introduction of an explanatory nomenclature.

Many of the more useful explanatory terms have been devised by Professor W. M. Davis, of Harvard, whose energies have been for many years focussed on the problem of developing a system of description which shall have the merit of brevity and which shall be explanatory and yet be geographical in that it does not distract attention from the present form to a consideration of geological processes belonging to the past.

Davis's point of view was stated by him in the following words in 1896: "An absolute, empirical description of the land-forms is unsatisfactory; it is arbitrary in arrangement, unsympathetic with the real life of the forms concerned, and generally very unsuccessful in its effort to see the facts that are to be described. For these reasons a description based on natural genetic conditions is to be preferred; it is rational in arrangement, thoroughly sympathetic with the real life of the land, and most aidful in bringing to sight and mind the characteristic elements of form; it enlivens physiography much in the same way that the principle of evolution has enlivened botany and zoology. It thus becomes the duty of the physiographer to acquaint himself with the development of land-features, not merely that he should understand the process and sequence of development, but chiefly so that he shall better perceive the products of development. . . . Knowing that existing forms are dependent on antecedent conditions, physiography might be defined, following Mackinder, as 'the study of the present in the light of the past.' The results of this study furnish us a knowledge of the earth, with which we enter geography" (32, p. 8).

Sixteen years later, in a presidential address to the Geological Society of America, he said:—

"Empirical concepts—I still speak especially regarding land-forms—are known only as far as direct observation can penetrate,

and they are therefore necessarily superficial in space, short-sighted in time, and rigid in definition. Explanatory concepts are known through and through, fore and aft: the farther side of the concept of a ridge is seen just as well as the near side, by the eye of the imagination, which takes any point of view that it desires; the inside of the ridge is seen as well as the outside, the past and the future forms of the ridge as well as the present form, for all these concepts are avowedly mental concepts only and not matters of fact. Explanatory concepts are, moreover, more elastic and adaptable, so that they may easily be made to match the facts of nature. Such concepts may be fanciful in the sense of not being necessarily counterparts of any natural forms: they may be erroneous in the sense of being incorrectly deduced from unsafe generalizations, and such chances of error must be recognized and guarded against. But the prime fact remains that explanatory concepts, deduced from general principles, are much more intimately and reasonably knowable than empirical concepts, or even than facts of observation usually are, and in this quality of being intimately and reasonably knowable lies their highest value. It is as if one located them by sighting from many different points along the path of time, and thus fixed their position by the intersection of many converging lines of sight; while empirical concepts are located only by a single line of sight running in one direction from the viewpoint of the momentary present" (34, p. 106).

"It is essential that the standardized type concepts with which one geographer is equipped, as well as the terms by which he names them, shall be known to his fellow geographers; for otherwise his descriptions will not be understood. If his colleague thinks of a hollow when he says 'hill,' they will gain no correct mental picture of the landscape that he tries to describe. Hence systematic nomenclature is of very great value. Geographical descriptions are indeed successful in direct proportion to the sufficiency of the observer's equipment and the possession of the same equipment in common by the observer and his hearers" (35, p. 28).

The chapters which follow are largely concerned with the development of a series of such standardized types. By the use of type concepts, which may sometimes be referred to in a very few words (*e.g.*, "dissected peneplain"), and more particularly by the use of the present tense in descriptive matter (34, p. 119; 38, p. 87)

attention may be directed to the actual geographical feature—the land-surface—rather than to the geological processes of the remote past.

Empirical Nomenclature. — Various writers have suggested the use of more or less strictly defined empirical terms either independently or along with explanatory terms such as will be introduced in the chapters that follow. Some of the empirical terms given by Mill in *The International Geography* are enumerated below. Comments by the present writer are enclosed in brackets.

Plain, and *plateau* or *tableland*, are to be used in the usually accepted sense, with the proviso that a highland composed of mountains and valleys alone—*e.g.*, the Pamirs—has no right to be termed a plateau.

The *hollow* is defined as a land-form that is bounded entirely or nearly so by higher land. A hollow is sometimes termed a "basin." It is unfortunate that valley-systems are also termed basins. A hollow amongst mountains and sloping towards the centre is an *intermont basin*. [This term is used also when the enclosing mountains are breached by a river which drains the basin.]

Cliff or *scarp* is a line of steep slope. The term *escarpment* is applied to a relatively steep slope which follows the line of strike of strata. [By many writers "escarpment" is confused with "scarp," and by some with the term "cuesta," which will be explained more fully later (Chapter VIII), and which denotes a salient feature including the escarpment and a gentler slope in the opposite direction.]

Mountains and *hills*: No arbitrary distinction between mountains and hills is satisfactory. *Peaks* are culminating-points. [It is to peaks that the term "mount" is generally applied as part of the name.]

A *valley* is viewed by Mill as "limited by the meeting lines of slopes." More definitely, "the meeting-place of two converging slopes is a *Thalweg*, valley-line, or stream-line." [It would be better to make it an essential feature of a valley that the valley-line should slope continuously in one direction. It would thus, under normal humid conditions, be always occupied by a single stream of water. This, however, traverses the use of the term in a number of geographical names. Many depressions popularly known as valleys,

which are of tectonic origin, would be more correctly termed "hollows" in Mill's sense.]

Longitudinal valleys are defined as between two parallel mountain-chains [better, parallel with the strike of rocks or the trend of folds or elongated tectonic blocks], while *transverse* valleys are across these.

The meeting-place of two diverging slopes is a *divide* or *water-shed*.

The *drainage area* of a river is "the whole space between the outer watersheds limiting the region draining into" it. [Davis defines a *valley-system* as "all the valleys from which the streams unite to form a single river," and a *river-system* as "a system of watercourses consisting of a river and all its branches and side streams."]

Literature of Geomorphology.—While it is the aim of this book to set forth the principles of geomorphology and to furnish the reader with a systematized scheme, or "series of standardized types," no claim to have exhausted the subject can be made: the treatment is necessarily elementary. Students of the earth sciences, as of every other branch of knowledge, should not be content to confine their attention to a single book. A short list of recent works on the subject and on portions of it will be found in an appendix. In addition to a selection of modern works which, being published as books, should be readily accessible in many libraries, the list contains the titles of some less easily obtainable papers and monographs. These are included on account of their outstanding value, and in acknowledgment of the writer's debt to their authors. Some of the books listed contain more complete bibliographies, which will be found most useful (see especially Penck, Tarr, De Martonne, and D. W. Johnson). As many of the explanations of New Zealand land-forms employed in this book have been advanced previously by the author in other publications, the titles of these are included in the list for further reference.*

---

* Copies of reprints of most of these papers are still available for distribution.

CHAPTER II.

PRELIMINARY NOTIONS OF GEOLOGICAL PROCESSES, ROCKS, AND ROCK-STRUCTURES.

Uniformitarianism. Geological processes. The material of the lithosphere: rocks. Rock-structures. Extended use of the term "structure" in geomorphology.

Uniformitarianism.—It is recognized that the present condition of the earth's surface is due in great part to the long-continued action of processes still in operation. Over a century ago it was asserted by the great geological thinker James Hutton that there is "no trace of a beginning, and no prospect of an end." Nowadays, however, such pronounced "uniformitarian" views, as they are termed, are regarded as extreme. It is no longer asserted that none of the forces now in operation have in the past varied in intensity, and the age of the earth—an age undoubtedly to be estimated in hundreds, if not thousands, of millions of years—is now regarded as a legitimate subject for investigation.

The importance of physical geology hinges, nevertheless, on the acceptance of the present as a "key to the past," and this key unlocks so many doors that we cannot but believe it is the right one.

Geological Processes.—Among the more important of the *processes* with which physical geology concerns itself are the work of rain, rivers, wind, waves, and ice, volcanic action, and earth-movements.

The raw materials on which the various agents work consist of layers and masses of *rock*, and, although the study of processes may, from one point of view, be regarded as a preliminary to the study of rocks, at least a rudimentary idea of rocks is required as a basis for the study of processes. Indeed, geological processes—including rock-making as well as rock-destroying processes—are to a great

extent cyclical. To begin with, the assumption may be made that rocks exist. These rocks are acted upon by certain geological agents which crumble and disintegrate them, producing *waste.* The waste is transported by geological agents—chiefly by running water—and is laid down—perhaps on the sea-bottom—as a layer of *sediment.* In the course of ages the sediment, which has in the meantime been hardened and consolidated, is *uplifted* by a geological process, so that the sea retires from it. It is now again rock, and subject again to the processes of destruction.

Though the majority of geological processes are cyclical, the stock of rocks resulting from the cyclical processes is continually augmented by the addition of rocks of *igneous* origin—volcanic lava, for example—and the first-formed rocks must have been of that kind.

The Material of the Lithosphere : Rocks.—It is only the superficial rocks that concern the student of land-forms. Geology, indeed, knows little about the nature of the materials forming the deeper, inaccessible parts of the globe.

Lithosphere is a term used to designate the outer shell of the solid globe, containing all accessible rocks. It is a somewhat better term than "crust of the earth," which is, however, often used, for the latter seems to imply belief in the now discredited theory that these rocks are merely a thin hardened crust or skin surrounding a mobile liquid interior.

The materials of the lithosphere are rocks and minerals. The fundamental units of geology are rocks, and rocks are made up of minerals, each of which is either a native element or a definite chemical compound of certain elements. Rocks are not necessarily hard ; the loose sand of a sandhill is technically a rock.

All rocks fall naturally into three great divisions, termed (1) *sedimentary*, (2) *igneous*, and (3) *metamorphic.*

Sedimentary rocks include all those that have accumulated on the surface of the earth (some of them under the sea) through the operation of water, ice, air, gravity, or organic agency. This class includes rocks formed from deposits of sediment, coarse or fine—namely, the conglomerates, sandstones, shales or mudstones, and slates, as well as limestones (most of which are composed largely of shells and other animal-remains), and coal, which is formed from accumulations of vegetable matter. Sedimentary rocks are, as a

general rule, disposed in layers, termed *beds* or *strata*,* piled one upon another (fig. 1). A thick stratum of one kind of rock is often termed a *formation*. On account of their *stratification* (arrangement in layers) this division of rocks is sometimes termed the *stratified* rocks. The rocks formed from mechanical sediment, as distinguished from organic material, are called *clastic*.

Igneous rocks are those that have solidified from the liquid state either beneath or on the surface of the earth. Those which have flowed out in sheets on the surface as lava before solidifying

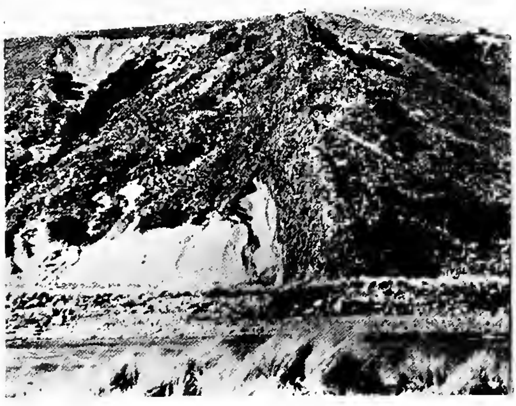
A. C. Gifford, photo.

Fig. 1.—Stratified rocks, Oamaru, N.Z. These strata, originally laid down horizontally, have been subsequently tilted into an inclined attitude, and still later their edges have been exposed to view by erosion in a sea-cliff.

are termed *volcanic* (Chapter XXIV). Lava-sheets may be found as beds alternating with beds of sediment, which have buried successive layers of lava. The fragmentary material ("volcanic ash") thrown out by volcanoes also forms strata, and when it has been spread and deposited by water may be interbedded and more or less mixed with clastic or organic sediment.

* Sing., *stratum*; pl., *strata*.

Igneous rocks that have solidified without reaching the surface are termed *intrusive*, each body of such rock being an *intrusion*. The smaller intrusions have generally solidified in fissures, often nearly vertical, forming thin sheets, which are called *dykes* (fig. 2). Thin sheets injected between strata are called *sills*. The rocks forming large intrusions are termed *plutonic*. The commonest is granite, and all have the coarse grain and texture termed *granitic*. Masses of plutonic rock are frequently so large that, when exposed



C. A. Cotton, photo.

Fig. 2.—Dyke of igneous rock, Trelissick Basin, Canterbury, N.Z.

by erosion, they form the land-surface over hundreds of square miles. Since in such masses there is no stratification, they are termed *massive*. Igneous rocks are, generally speaking, harder and more resistant to the processes that are wearing down the land than are the sedimentary rocks associated with them.

Metamorphic rocks have been formed from either sedimentary or igneous rocks, chiefly by the long-continued action of heat and pressure. These have caused a rearrangement of the elements of

the rocks into new minerals, which are generally of flaky form. On account of the abundance of mica and the arrangement of the minerals in layers (foliation) most metamorphic rocks (schists) are softer and more easily broken and worn away than are igneous rocks (fig. 3).

W. D. Reid, photo.

FIG. 3.—Foliated metamorphic rock (mica schist) outcropping on the Rock and Pillar Range Otago, N.Z.

Rock-structures.—All rocks are subject to movements of various kinds, and so they do not remain in the positions and attitudes in which they were formed (fig. 4). Stratified rocks, originally laid down horizontally or nearly so, are sometimes found

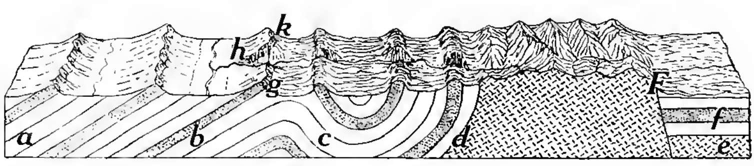


FIG. 4.—Diagram of structures. *ad*, *f*, stratified rocks; *de*, massive rock; *ab*, homocline; *bc*, anticline; *cd*, syncline; *f*, strata still horizontal; *F*, fault; *ghk*, outcrop of stratum *b*.

still in that attitude, though they may have been uplifted bodily, but far more often they are tilted or bent (*folded*) into arches and troughs, termed *anticlines* and *synclines* (figs. 4–6). Strata

C. A. Cotton, photo.

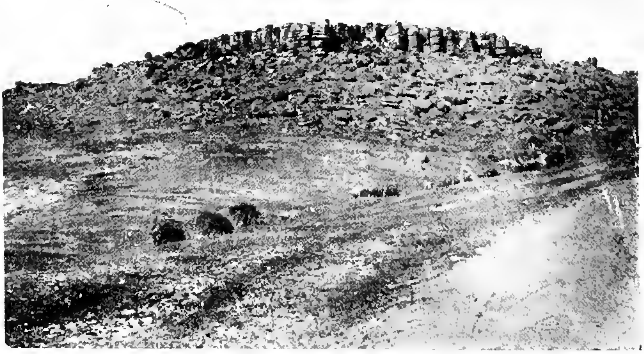
FIG. 5.—Small anticline exposed in a sea-cliff, Fitzroy Bay, Wellington. N.Z

C. A. Cotton, photo.

FIG. 6.—Limestone stratum folded into an open syncline, Weka Pass, Canterbury, N.Z

C. A. Cotton, photo.

FIG. 7.—Outcrop of limestone, Waipara district, Canterbury, N.Z.



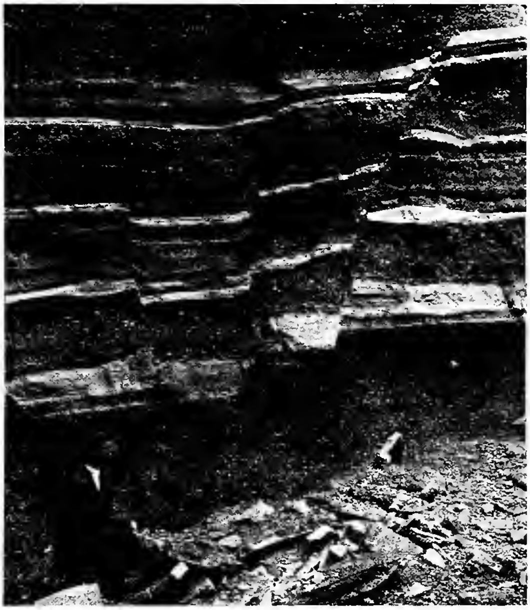
C. A. Cotton, photo.

FIG. 8.—Outcrop of jointed volcanic rock, near Kokonga, Otago, N.Z.

which are inclined (which *dip*) constantly in one direction form a *homocline** (fig. 4). In some cases the beds are quite vertical.

Sheet-like igneous rocks exhibit folding like sedimentary strata, but such structures are not obvious in massive rocks.

The band traced on the surface of the ground by a rock layer is its *outcrop* (figs. 4, 7, 8), and the direction of a band which would be traced on an imaginary horizontal surface is its *strike.* The strike



C. A. Cotton, photo.

FIG. 9.—Miniature faults, Takapuna, Auckland, N.Z.

is at right angles to the direction of steepest inclination, the *dip*, of the stratum.

Faults (figs. 4 and 9) are surfaces of fracture in the rocks, along which movement has taken place, all on one side of the break having moved relatively to all on the other side. A break in the surface of the ground accompanies the formation of a fault in

* The term *monocline* is sometimes used in this sense. The use of the term *homocline* is advocated by R. A. Daly.

the rocks beneath, but if the fault is an old one the chances are that erosion has removed all trace of it at the surface (fig. 10), or has developed relief forms in connection with it which are quite different from the original break (Chapter XIII).

Joints (figs. 8 and 11) are fissures or cracks in rocks. In almost every rock there are joints, and frequently several systems of joints intersect, dividing the rock into large or small pieces.

C. A. Cotton, photo.

Fig. 10.—A fault exposed in the gorge of the Dee Stream, Clarence Valley, N.Z. The steeply-inclined light-coloured band in the centre is the line of the fault. Relatively old rocks (on the left) are brought against younger rocks (on the right), indicating a movement of thousands of feet, and yet in the crest-line of the spur there is scarcely a break at the fault-line.

Joints, though mere cracks, and not open fissures, are of great assistance to eroding agents, weakening the rock-masses and allowing water to penetrate them.

Extended Use of the Term "Structure" in Geomorphology.—As generally used in geomorphology the term structure is more comprehensive than in geological writings. As used in Davis's all-inclusive formula for explanatory description of land-forms—"structure, process, and stage"—it "indicates the product of all *constructional* agencies. It includes the nature of the material, its mode of aggregation, and even the form before the work of erosive agencies begins. In other words, it stands for that upon which erosive agents are, and have been, at work" (Fenneman).

C. A. Cotton, photo.

FIG. 11.—Several systems of joints intersecting in sedimentary rock, Wadestown, Wellington, N.Z.

CHAPTER III.

NORMAL ERODING AGENTS AND THEIR WORK.

Erosion. Weathering: the work of rain and associated agents. Rock-breaking by physical agencies. Talus slopes. Rock-breaking by organic agencies. Rock-decay. Residual clay. Spheroidal weathering. Depth of weathering.

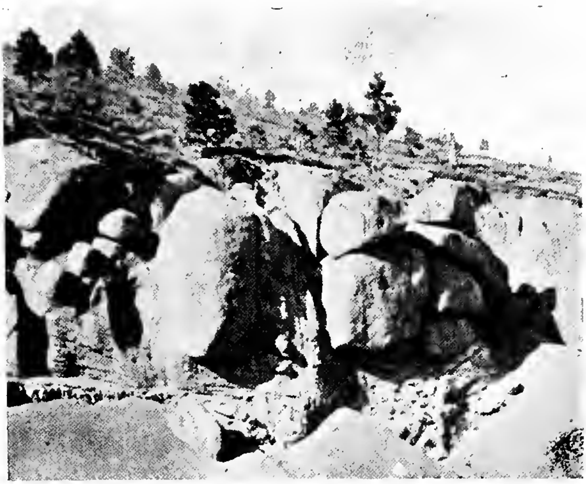
Erosion.—All rock-masses that are exposed at the surface of the earth are subject to constant chemical and mechanical action, by which they are decomposed and worn away. *Erosion* is a comprehensive term denoting the sum of such processes, and *denudation* as generally applied is synonymous with erosion. By these processes the lithosphere is said to be *eroded* or *denuded*. The majority of surface features—viz., hills, valleys, &c.—are the work of erosion, which, however, is not a finished process but is still in progress. The material that is removed as waste by erosion goes to form new sedimentary rocks.

There are three natural divisions of erosion—viz., (1) *rock-breaking*, (2) *rock-decay*, and (3) *transportation*.

The most important of the eroding agents are running water, rain, certain physical and organic processes, wind, glaciers, and wave-action. Wind and glaciers are important only within strictly limited areas, while wave-action is important only around the margin of the land. The remaining processes—running water, rain, and certain associated physical and organic processes—are responsible for the erosion now in progress over the greater part of the surface of the habitable lands. Hence they are termed the *normal** processes.

Weathering: the Work of Rain and Associated Agents.—The work of rock-breaking (disintegration) and rock-decay (decomposition and solution) accomplished by rain and associated processes is

* "The term 'normal erosion' is plainly open to criticism on the ground that one mode is just as normal as another, but no other satisfactory term has been proposed" (Fenneman).



C. A. Cotton, photo.

Fig. 12.—Granite suffering disintegration and crumbling into coarse sand, Rocky Mountains, Colorado, U.S.A.

C. A. Cotton, photo.

Fig. 13.—Exfoliation from an exposed face of limestone, Trelissick Basin, Canterbury N.Z.

L. Cockayne, photo.

FIG. 14.—Dome-shaped mountain-top produced by exfoliation of massive rock (granite), Frazer Peaks, Stewart Island, N.Z.

C. A. Cotton, photo.

FIG. 15.—"Whale-back" surfaces due to exfoliation from sandstone, Monkey-face Hills, Marlborough, N.Z.

termed *weathering*. In a discussion of weathering the two phases, rock-breaking and rock-decay, may be considered separately.

Rock-breaking by Physical Agencies.—In arid regions and on mountain-tops there is a great daily range of temperature, the difference between the temperatures of night and day amounting sometimes to 100 degrees of the Fahrenheit scale. Exposed surfaces of rock are thus rapidly heated and cooled. As the different

B. C. Aston, photo.

FIG. 16.—Newly broken blocks on a mountain-top. Mount Tapuaenuku Kaikoura Range, N.Z.

mineral constituents of a rock expand differently when heated, and as there are not generally any spaces to accommodate mineral grains expanding more than their neighbours, enormous strains are set up by such differential expansion. The surface of the rock thus either crumbles to coarse sand (fig. 12), or separates as large flakes. The latter process is termed *exfoliation* (fig. 13).

Some smooth, dome-like hills, and even mountains, owe their form to exfoliation on a large scale from the surface of large masses of strong rock free from joints. Smooth "whale-back" surfaces of bare rock in Stewart Island (see fig. 14), and also on the Monkey-face Hills, near Greenhills, Marlborough (see fig. 15), appear to have originated in this way.

C. A. Cotton, photo.

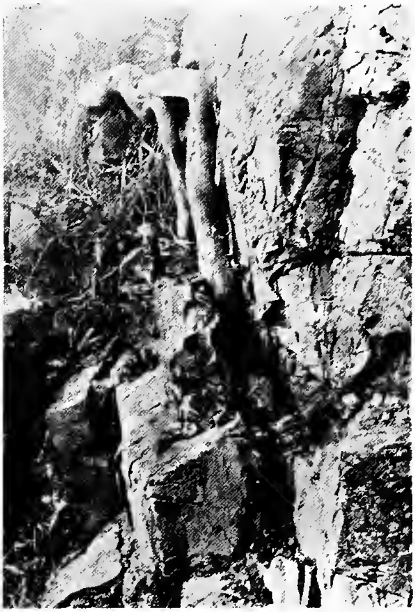
Fig. 17.—Talus slopes below cliffs of crumbling mudstone, Clarence Valley, N.Z. The mudstone fragments are delivered into and carried away by, a stream flowing across the foreground

Daily temperature-changes do not penetrate far into a rock, and so disintegration due to this cause is a surface phenomenon. Where the waste accumulates it blankets the rock, and thus protects it from further disintegration, but owing to the removal of the waste from desert surfaces by wind and from mountain-peaks by gravity fresh surfaces are there constantly exposed, and disintegration goes on apace (fig. 16).

Another physical agency that is very effective in rock-breaking is the freezing of water in crevices. This also is very effective on mountain-peaks. Freezing water expands and widens the crevice in which it lies, and constant repetition of the process eventually prises off a rock-fragment.

Talus Slopes.—Streams of angular rock-fragments forming *screes* or *talus slopes* below exposed rock-outcrops on mountain-sides testify to the activity of the rock-breaking processes on the mountain-tops. The rubble that slips down these talus slopes is delivered to streams, which are constantly removing it (fig. 17). Hence the presence of such slopes proves that the supply of newly broken waste is abundant.

Rock-breaking by Organic Agencies.—A certain amount of rock-breaking is accomplished by plant-roots penetrating crevices (fig. 18), and also by burrowing-animals such as rabbits. A great quantity of soil is finely comminuted and deposited on the surface by earthworms, which pass it through their bodies. Such fine material is readily washed away by the run-off during rain-showers.



C. A. Cotton, photo.

FIG. 18.—Rock-crevice enlarged by the growth of tree-roots, which are prising off slabs of rock, Miramar Peninsula, Wellington, N.Z.

Rock-decay.—This second component of weathering involves chemical processes and is largely the work of rain-water, accomplished during its downward passage through the soil and subsoil, though bacteria are also active in the soil. The activity of rain-water is due mainly to the chemical and solvent action of dissolved substances, chief among which are oxygen and carbon dioxide. These gases are dissolved from the atmosphere by the falling rain, and

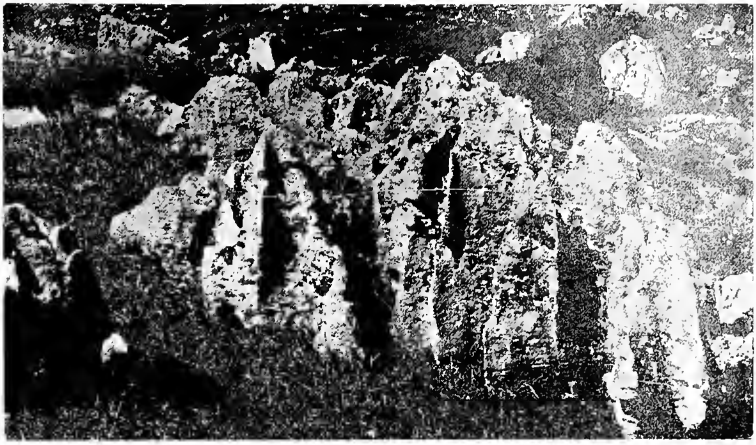
during its passage through the upper layer of soil the water takes up a further amount of carbon dioxide resulting from plant-decay. Above the level of water saturation, air is present in the crevices of the rocks, and the oxygen of this aids in producing rock-decay. The most important chemical processes involved in the attack made by rain-water on the mineral constituents of rocks are oxidation,

C. A. Cotton, photo.

FIG. 19.—Limestone outcrop fluted by the solvent action of rain, Waro, Whangarei, N.Z.

hydration, and carbonation. These are accompanied by solution either of original constituents of the rock or of substances separated from rock-constituents by chemical action.

The simplest action of rain-water is solution of limestone, a rock consisting of a single mineral, calcite, the chemical composition of



C. A. Cotton, photo.

FIG. 20.—Limestone outcrop fluted by the solvent action of rain, Ruakokopatuna Valley, Wairarapa, N.Z.

C. A. Cotton, photo.

FIG. 21.—Solid rock (below) passing up into residual clay and soil, Tinakori Hills, Wellington, N.Z.

which is carbonate of lime. This compound is soluble in water containing carbon dioxide. The effects of solution by rain-water are to be seen on all outcrops of pure limestone, which show a furrowed surface due to rain-water collecting as streams and deepening by solution the grooves in which it flows (figs. 19 and 20).

Residual Clay. — The effects of rain in producing rock-decay are to be seen in practically all rocks, but especially in igneous rocks with abundant silicate minerals. These latter are broken up, the alkalies present in them are removed in solution as carbonates, the alumina, combined with some of the silica, is hydrated and forms clay. The iron is separated from the compounds in which it is present in the rock and is oxidized to the ferric state and hydrated to form the mineral limonite, which stains the clay yellow or brown. The grains of minerals such as quartz and white mica, which are but very slightly acted upon by rain-water, remain scattered through the clay. In this way is formed *residual* clay, so called because it is the residue resulting from the decay of a rock.

L. I. Grange, photo.

FIG. 22.—Spheroidal residual boulders formed by weathering of volcanic rock, Green Island, Dunedin, N.Z.

Weathering is most complete at the surface of the ground. A little below the surface the rock is only partially weathered, and some distance down there is fresh or unweathered rock (fig. 21). This is easily understood when it is remembered that weathering works downward from the surface, and also that the surface of the ground is being worn away. A layer below the surface now will at some future time be at the surface, but by that time it will be more thoroughly weathered than it is now.

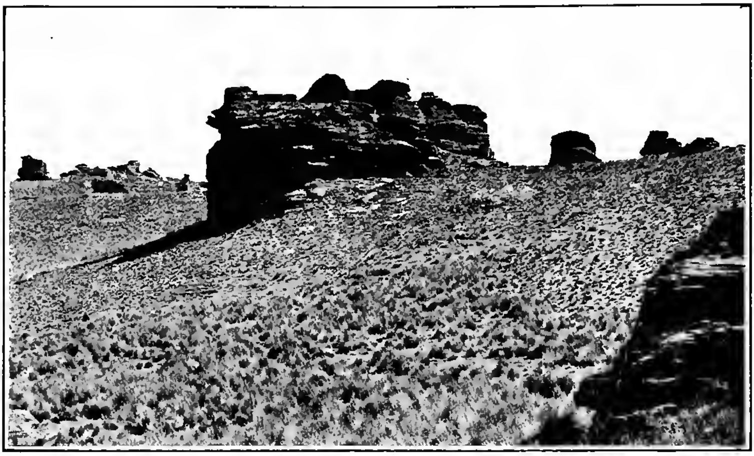
Spheroidal Weathering.—Rain-water passing down through rock makes its way along the natural crevices or joints present. When these are rather widely spaced they separate compact blocks of rock,

L. Cockayne, photo.

Fig. 23.—A tor of granitic rock, Frazer Peaks, Stewart Island, N.Z.

C. A. Cotton, photo.

Fig. 24.—Schist tors on Rough Ridge, Otago, N.Z.



C. A. Cotton, photo.

FIG. 25.—Schist tor giving an architectural effect, Rough Ridge, Otago, N.Z.

F. G. Radcliffe, photo.

FIG. 26.—High-water rock platforms, the "Old Hat," Russell, Bay of Islands, N.Z

which slowly weather on all their surfaces. As sharp angles on such blocks are attacked from two sides, they become rounded off. Hence as the weathered layer around the outside becomes thicker the diminishing core becomes more and more nearly round, or spheroidal. In a residual clay such spheroidal cores are frequently abundant (fig. 22), and when some of the clay is washed away they may lie on the surface. They must not be taken for stream-worn pebbles. The huge boulders forming singly or in piles the salient features known as *tors*, sometimes resembling ruined masonry, which surmount many plateaux formed of granitic rocks have originated in a similar way (see fig. 23). In the dry area of Central Otago tors of mica schist break the monotony of the upland plateaux. Where the schist-foliation is nearly horizontal they also have the appearance of masonry (see figs. 24, 25).

Depth of Weathering.—The depth to which weathering proceeds depends upon the depth to which rain-water can sink vertically before reaching a continuous body of water (the *ground-water*). The *level of ground-water*, or the *water-table*, below which the rocks are saturated and all cavities are filled with water is deeper on hills than on flat country, and, other things being equal, is deeper also where the rocks are shattered or porous. The ground-water level also varies with the seasons, being close to the surface after long-continued rains. It is the deepest level reached by the water-surface that sets a limit to the depth at which ordinary rock-decay can take place.

Though higher farther inland, at the seashore the water-table coincides with high-tide level. Owing to the slowness with which the water seeps out of the rocks, its level cannot sink appreciably lower between tides. In sheltered inlets of the North Auckland coast this leads to a striking demonstration of the rapidity of weathering and of the relation of the lower limit of rock-decay to the water-table (Bartrum, 25). The feeble waves on those sheltered waters readily remove weathered waste but have not much power to erode fresh rock, and so, as the weathered rock is removed by the waves, a broad, nearly horizontal, rock platform very little below high-water level is rapidly developed bordering the shore (fig. 26; see also Chapter XXVII).

CHAPTER IV.

NORMAL ERODING AGENTS AND THEIR WORK (*continued*).

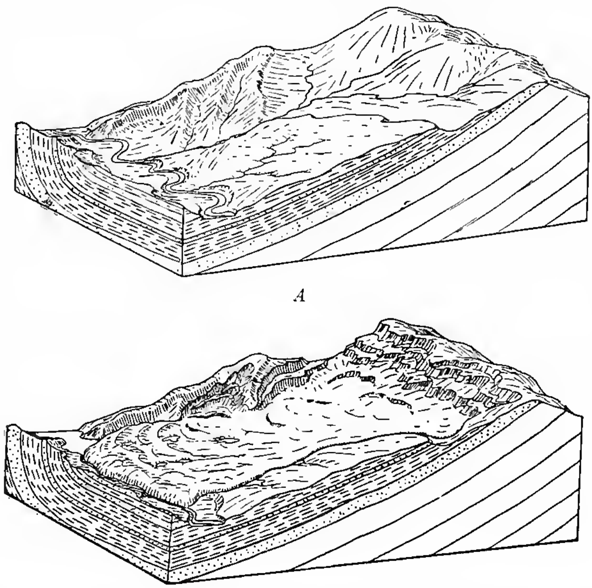
The mantle of waste. Soil-creep. Transportation. Mechanical work of rain. Rivers. Corrasion and transportation by running water. Chemical corrasion and transportation in solution. Mechanical corrasion and transportation in suspension. The size of fragments carried. The quantity of waste transported.

The Mantle of Waste.—On all surfaces except the steepest, from which the broken fragments fall or stream down to form talus slopes below, the waste resulting from weathering (particnlarly rock-decay) accumulates as a mantle of soil, clay, and partially decayed rock-fragments. It is the presence of this waste that allows of the growth of vegetation; and vegetation, in its turn, when present, helps to bind the waste and retard its removal, and so to increase the thickness of the accumulation.

The thickness of the waste-mantle does not, however, increase indefinitely, thongh rock-decay continues, for the upper layer is continually being removed. This removal of waste, which results in a general lowering or wasting-away of the land-snrface, is partly effected by washing-away of fine particles by running water in wet weather (see p. 35). There are, however, other means of removal. *Landslips*, for example take place when sections of the waste-mantle become so saturated with water that they are too fluid to remain on the slope on which they have been formed. Whole hillsides thus slip away, forming streams of rock and soil, sometimes miles in length, which move somewhat like glaciers (figs. 27–29). Snch landslips leave scars bounded by arcuate scarps (fig. 28). The waste when it comes to rest forms a highly irregular, hummocky surface with undrained hollows (fig. 29). Much of the waste slips into streams which eventually carry it away, though generally their valleys are blocked for a time, so that ponds or lakes are formed.

In various parts of New Zealand scars left by landslips and hummocky topography formed by the slipped material are fairly common. In North Auckland the "hydraulic limestone" formation is so unstable that the opening of road and railway cuttings is sufficient to cause whole hillsides to slip away, though the relief is low and the slopes are gentle (figs. 28, 30).

Soil-creep.—There is a much more general, though imperceptible, movement of the waste-mantle on slopes always in progress, which



A

B

FIG. 27.—Diagram of a landslip (the Gros Ventre Slide, Wyoming, U.S.A.). *A* is a restoration of the landscape as it was before the slip occurred; *B* shows the landslip topography. (After Blackwelder.)

accounts for the removal of a great part of the waste. This movement has been termed *creep* (Davis). The agency at work is gravity, but the motion is not strictly comparable to the flow of a fluid. Small to-and-fro movements of waste fragments are always going on as the result of alternate heating and cooling, freezing and thawing, wetting and drying. Owing to the constant pull of gravity, there is a preponderance of downhill over uphill movements, and as a result the waste creeps slowly downhill (fig. 31). Evidence

J. Wood, photo.

FIG. 28.—Landslip in the "hydraulic limestone" formation, North Auckland, N.Z. The whole hillside below the scarp above which the man is standing is in motion. The backward tilting of strips between the scarps formed by fissures ("crevasses") in the slipped material is characteristic.

R. Speight, photo.

FIG. 29.—Landslip topography, Motunau, North Canterbury, N.Z.

of this may be seen in the downhill sag of the edges of the layers of partially weathered rocks, which is sometimes termed "outcrop-curvature."

"A layer of unconsolidated material resting on a gentle slope holds its position (1) because the particles are arranged so as to

J. Wood, photo.

Fig. 30.—A newly-made cutting closed by a landslip, in the "hydraulic limestone" formation, North Auckland, N.Z.

support one another, and (2) because one particle cannot slide on another without developing friction. Spherical frictionless particles would flow on the faintest of slopes, and subangular frictionless particles would flow on a moderate slope. Whatever diminishes friction promotes flow. Whatever disturbs the arrangement of particles, permitting any motion among them, also promotes flow, because gravity is a factor in the rearrangement, and its tendency is down the slope. Violent agitation by an earthquake suspends for the time the structural arrangement, surcharge by water greatly reduces

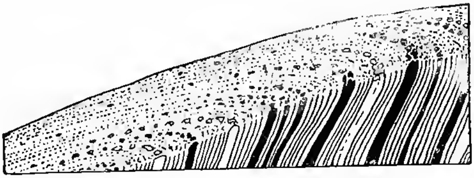
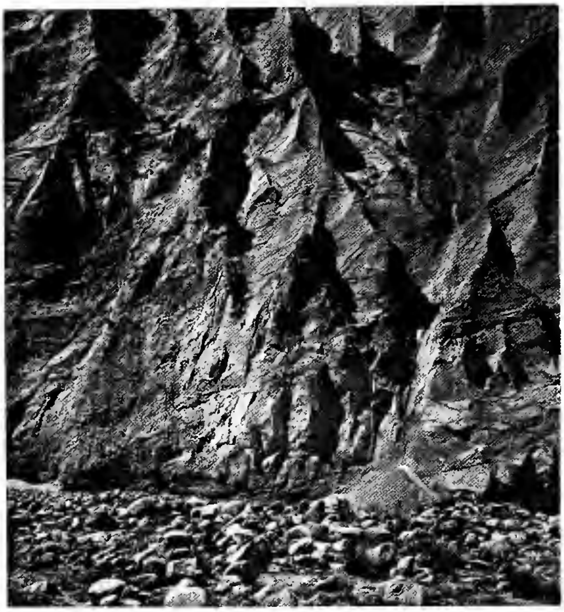


Fig. 31.—Diagram of the downhill creep of waste. (After Davis.)

friction, and each of these may cause flow, the flow phenomena being of the landslide type.

"In creep the chief disturbing agencies are expansion and contraction, and these are caused by freezing and thawing, heating and cooling, wetting and drying. If expansion were equal in all directions, and extended indefinitely downward, the arrangement of the particles — or the structure of the formation — would not be affected; but dilatation is resisted in all directions except outward, and expansion in a single direction modifies the structure. The



R. Speight, photo.

Fig. 32.—"Badland" sculpture in marl rock, Broken River, N.Z. For the characteristic appearance of "badland" topography see also fig. 196, where, however, it has been produced by the extremely rapid erosion of gravel previously kept stable by vegetation.

structure is again modified during the ensuing contraction, and during both changes gravity enters as a constant factor tending downhill" (Gilbert, 47).*

* The rate at which a slab of stone will creep down the inclined surface of another slab as a result of expansion and contraction due to alternate heating and cooling of the upper slab when exposed to sunshine was investigated by C. Davison (*Quart. Journ. Geol. Soc.*, vol. 44, pp. 232–38, 1888).

Transportation.—The chief agents removing the waste produced by weathering are rain and running water. Running water is the more effective of the two, but rain-drops as they fall loosen particles of fine waste, mix up with them and so take them into suspension as mud, and thus co-operate with running water, which, gathering as temporary streams on the surface, washes the mud away into the channels of larger streams. Fine material is thus removed not only from bare ground, but also from pasture-land, to the surface of which a great quantity of fine material is constantly being brought up by earthworms.

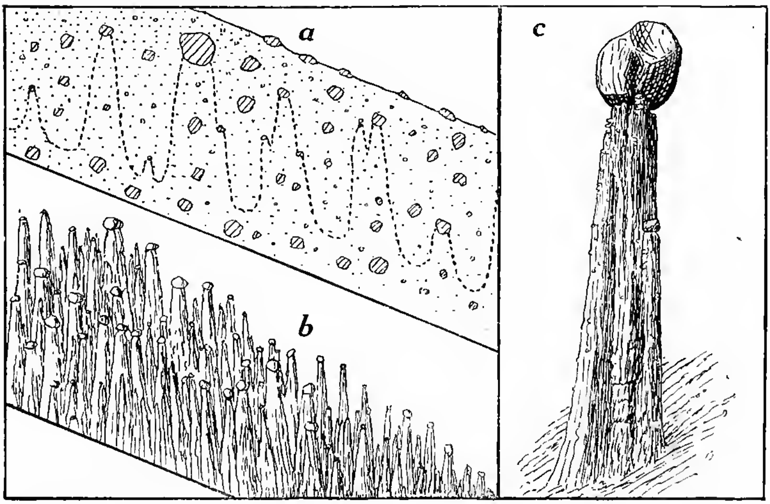


FIG. 33.—Earth pillars. *a*, section of a clay containing boulders of various sizes, showing the profile of the surface before and after etching by rain; *b*, a group of earth pillars; *c*, earth pillar at Bozen, Tyrol (drawn from a photograph).

Mechanical Work of Rain.—Bare ground, especially when consisting of clay, is sculptured by rain-wash into innumerable closely-spaced, steep-sided ridges and valleys of small size, producing a type of almost impassable country termed "badlands." "Badland" sculpture is common on clay ground, because the clay is practically impermeable, almost all the water that falls as rain running off immediately (fig. 32).

An example of the work of rain-drops is afforded by *earth pillars* (see fig. 33). These are formed under special conditions—namely,

where the rain-drops fall vertically in sheltered situations upon material consisting of clay with embedded boulders. As the surface is worn down, the boulders protect the clay immediately beneath them from the impact of falling drops, and so each boulder becomes the cap of a column of clay.

The small earth pillars shown in fig. 34 were formed by the action of rain-drops falling on a path recently made of stones and earth.

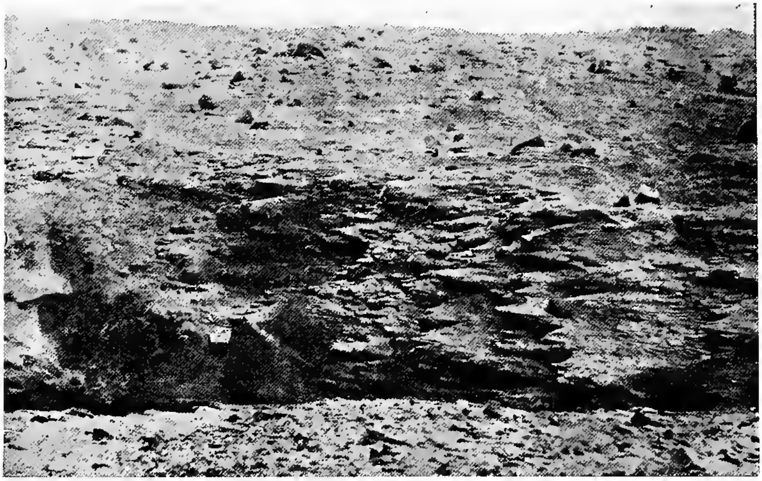
It must not be supposed that rain is particularly active as an eroding agent when falling vertically; but under favourable conditions vertically falling rain-drops can cut earth pillars, which afford a demonstration of the universal erosive action of rain.

Rain, indeed, does most erosive work when the impact of the drops is greatest—that is, when the drops are large and, especially, when they are driven by wind. In the neighbourhood of Wellington, where showers of wind-driven rain occur frequently, the sides of cuttings often exhibit miniature earth pillars in a nearly horizontal attitude. These are particularly well developed in a cutting at Seatoun (fig. 35) which passes through a sandy clay containing fragments of rock, the result of mixture of blown sand with residual waste streaming down a hillside.

Rivers.—When rain falls, generally some of the water runs off the surface immediately. The proportion of this *run-off* to the total precipitation is very variable, being obviously greatest with heavy rain and when the ground is already saturated. It forms wet-weather rills in great numbers, which flow into the more permanent streams or rivers and furnish a part of their flow. If this were the only source of supply, however, all streams would be intermittent; none would be permanent. The remaining portion, sometimes 75 per cent. or more, of the water that falls as rain sinks into the ground. Some of this water is returned to the surface by capillarity, and evaporates either directly or through the action of vegetation; but a varying proportion, after sinking some distance vertically through the unsaturated surface material, joins the continuous body of ground-water. It is from the ground-water that rivers receive the whole of their water in dry weather, and a proportion of it in all seasons. The ground-water is not stagnant, but moves slowly through the minute spaces between the grains of the rocks of more open texture, and through the fissures in more

A. C. Gifford, photo.

FIG. 34.—Small earth pillars formed on a newly-made path through the forest, Lake Ada, N.Z.



C. A. Cotton, photo.

FIG. 35.—Miniature, nearly horizontal earth pillars in a cutting on the Seatoun-Breaker Bay Road, Wellington, N.Z.

compact rocks, towards an outlet at a lower level. This outlet may be a spring, but more commonly the water simply oozes, or *seeps*, out along the beds of streams below the surface of the running water.

Owing to friction of the narrow passages, which retards the flow of ground-water, it does not get away quickly. This leads to two important results: first, the supply of water to streams is maintained through long periods of drought; and, secondly, the water-table does not become flat, or even nearly flat, but remains arched up under hills, where there are always mounds of ground-water (see fig. 36), the water-table gradually sinking during dry weather, but rising so as to approach the surface again with every rain.

Not all the water of a river reaches the sea. Evaporation goes on from the free surface, and this loss is especially important in arid

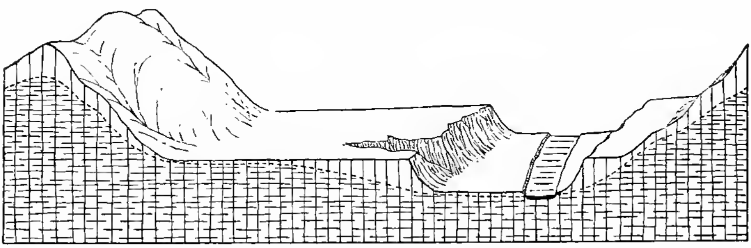


Fig. 36.—Diagram showing the ground-water (shaded), and the water-table (the broken line) underlying a river-valley. Note that the water-table intersects the surface at the level of the water in the river.

districts where rivers receive no tributaries. It is owing partly to this evaporation, and partly to loss through soakage into the loose material of desert plains, that many rivers in arid countries dwindle to mere threads or strings of waterholes, and finally disappear altogether, as in the interior of Australia. Other rivers under like conditions flow into lakes without outlets, evaporation from which balances the inflow.

Corrasion and Transportation by Running Water.—However they originate and whatever ultimately becomes of them, all rivers are, while they flow, capable of doing erosive work. This is of two kinds—namely, *corrasion* (or cutting) and *transportation*.

The corrasion is of two kinds—namely, *chemical* and *mechanical*; and the material transported is carried in two ways corresponding respectively to these—namely, in *solution* and in *suspension*.

Chemical Corrasion and Transportation in Solution. — Rivers undoubtedly act chemically on the material in their channels and thus take quantities of rock-constituents into solution, but, as the water which a river receives from springs and from percolation along its bed already contains substances in solution, it is not possible to say in any particular case how much of this kind of work is accomplished by the river.

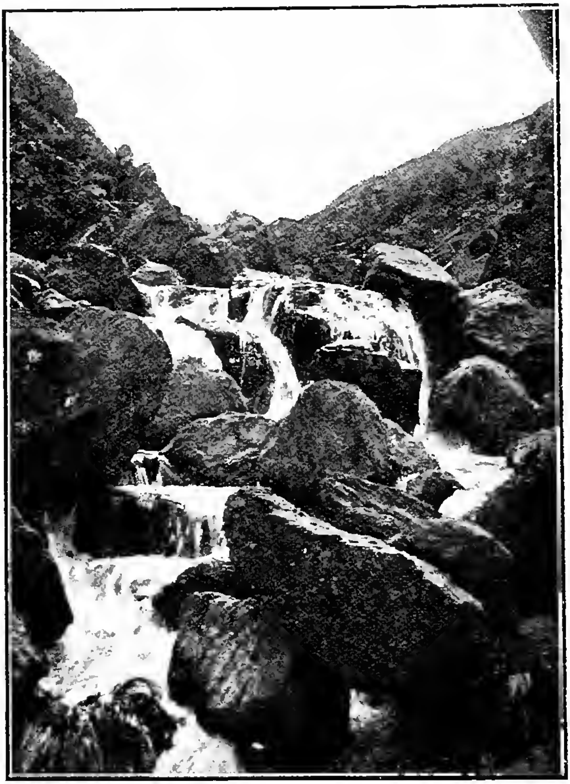
In the aggregate the amount of dissolved substances actually carried by river-waters is very great, and represents a large quantity of material removed from the land-surface. The average is about 18 parts in 100,000 of water. About half is carbonate of lime. Next in abundance is magnesium carbonate; and there are sulphates and chlorides of lime, magnesia, soda, and potash, as well as some silica, and other substances in less amount.

Estimates have been made of the quantity of material carried annually to the sea by various great rivers. The Mississippi, for example, carries 136,400,000 tons. The rate of lowering of the whole surface of the United States due to removal of substances in solution has been calculated to be 1 ft. in 24,000 years. A similar calculation for England and Wales gives a rate of 1 ft. in 13,000 years.

It is from the salts carried down by rivers that the salt of sea-water is derived, and also the substances which are deposited from salt lakes as "chemical deposits." The lime carried to the ocean is largely used up in making the skeletons and shells of marine animals.

Mechanical Corrasion and Transportation in Suspension.— Some solid material is carried into streams by rain-wash, and coarser fragments are derived from talus slopes and landslips and are carried down valley-sides by soil-creep. Water without solids in suspension cannot exert a cutting or scouring action, but when solid fragments are carried along they wear away the banks and bed of the river and also one another. Thus more material is always being removed by the river, and the fragments are being rounded. This is particularly the case with pebbles of hard rock, which become nearly spherical after being rolled and carried a few miles along a river-bed. In this way *river gravel* originates. The wearing action is much less marked on finer particles—those which are termed *sand* and *mud*—because the films of water which cling

to them by surface tension act effectively as cushions and prevent actual grinding of the grains. The grains of sand that have been carried by water only are, therefore, always somewhat angular, and they may thus be distinguished from wind-carried sand-grains—*e.g.*, those of deserts—which are much more perfectly rounded.



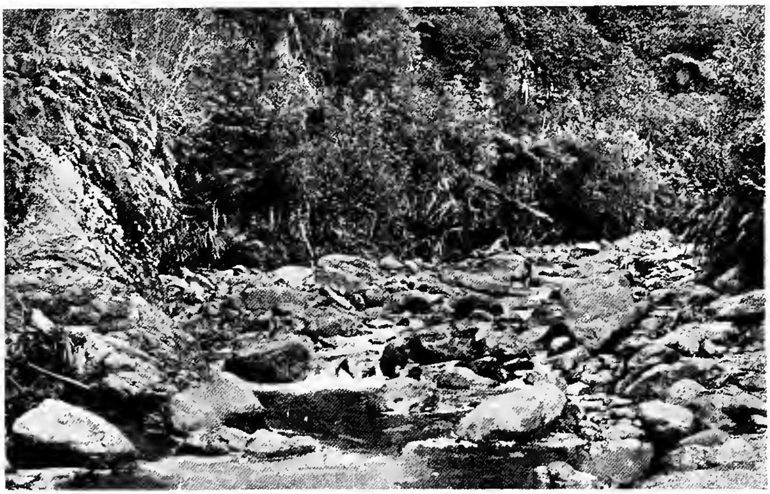
J. Park, photo.

Fig. 37.—Angular boulders in a mountain-stream, Central Otago, N.Z. (From *N.Z. Geol. Surv. Bull. No. 5.*)

Enormous quantities of gravel, as well as sand and mud, are brought down by many New Zealand rivers in all parts of the country, but especially by those draining eastward from the mountains of Canterbury. There the exposed parts of the river-beds are composed of typical stream-worn gravel. The constituent pebbles are rounded, but flat sides remaining here and there

indicate that the pebbles have been formed by the grinding-away of the corners and edges of fragments originally angular and bounded by flat joint-surfaces. If the pebbles are traced to their sources it is found that farther and farther up-stream they are less and less rounded until, among the mountains, the talus slopes of rough, angular rubble—the so-called "shingle-slips"—are reached, which are the source of supply of waste to these rivers.

In general, in small streams and near the heads of streams, where the waste has not travelled far, rounding of boulders and pebbles is incomplete (figs. 37, 38).



C. A. Cotton, photo.

FIG. 38.—Coarse waste (boulders), partly rounded, in a tributary of the Ngakawau River, western Nelson, N.Z.

The Size of Fragments carried.—The size of fragments that can be carried in suspension by flowing water depends on the velocity of the stream. A sluggish stream with a velocity of 0·17 mile per hour will be capable of carrying only the finest silt, while one flowing two miles per hour (a fairly rapid stream) will sweep along pebbles the size of eggs (A. Geikie). The shape also of fragments has an influence on the size that can be carried. Thus flake-shaped fragments of relatively large size will be carried, for they sink but slowly. For fragments of the same shape the transporting power of streams varies as the sixth power of the velocity.

In any stream there is a thread of maximum velocity at or near the surface and, where a stream is straight, in the centre, but displaced towards one side or the other where there are curves. The velocity diminishes progressively from this thread towards the bottom and sides, where the water is retarded by friction. It is not the maximum or even the mean velocity of a stream that determines the maximum size of fragment that can be carried, but rather the minimum—that is to say, the velocity of the bottom water, for the largest pebbles always slide or roll along the bottom.

Fragments in suspension do not, of course, float. Each fragment is always sinking, slowly or rapidly, according to its size, shape, and specific gravity, which affect the resistance offered to sinking by the viscosity of the water. In running water, however, the motion is not uniformly forward. Owing to irregularities in the stream-bed, eddies and cross-currents are frequent, and fragments remain in suspension owing to their being lifted from time to time by upward currents with a velocity greater than that with which the fragments are sinking.

While the larger stones are rolled along the bottom, very large boulders are moved along by torrents in another way. Their forward motion is not continuous. Occasionally, during floods, the stream scours away the gravel on which a large boulder rests, leaving it badly supported. After a time, pressed onward by the stream and unsupported in front, it rolls forward a short distance, and this process is repeated many times, though perhaps at long intervals.

The Quantity of Waste transported.—The amount of waste actually carried by a stream depends not on its carrying-capacity alone, but also on the amount available. Sometimes solid material as much as one-tenth of the weight of the water is carried by small streams in flood. The amount may fall as low as one eight-thousandth. In the case of the Mississippi the average is about $\frac{1}{1800}$ by weight. The total amount of suspended material removed by the Mississippi in a year is 340,500,000 tons. (This is additional to the 136,400,000 tons removed in solution.) By chemical and mechanical erosion the whole drainage area of the Mississippi is lowered at the rate of 1 in. in 500 years. The rate of lowering for the whole of the United States is calculated to be 1 in. in 760 years.

Data on which an estimate of the annual lowering of the surface of New Zealand by erosion might be made are not available.

CHAPTER V.

THE NORMAL CYCLE.

Normal erosion. The cycle of erosion. The cycle of erosion in a simple case. Consequent drainage. Youth. Characteristics of young valleys. Potholes. Cañons. Falls and rapids. Lakes.

Normal Erosion. — The subaerial, as distinguished from marine, eroding agencies fall in two groups, *normal* and *special* (Davis, 4, p. 288), and it is by the normal group, running water and the weathering processes, that the shaping of the land-surface is mainly effected.

Wind erosion and ice erosion (both of which are distinguished as "special" agencies) seldom, if ever, work alone. Even in arid deserts, where wind would seem to be the most important eroding agent, occasional showers of rain occur, and while these last they are very violent, giving rise to intermittent streams of great eroding-power. In frigid regions also, while ice erosion is dominant, normal weathering is active on all exposed rocks. The normal agents, however, can work without help from the special agents; and upon practically all the habitable portions of the land-surface it is the normal agents alone that are now active.

It is now universally recognized that, generally speaking, valleys are the work of the streams that flow in them (p. 6). This true explanation of the origin of valleys (and consequently also of hills or ridges, which are merely the residual portions of the rock-mass sculptured by erosion) gained acceptance only in the nineteenth century. The arguments in favour of it were first clearly stated in 1802 by Playfair, who relied for proof on what is now termed Playfair's *law of accordant junctions*, the principle of the adjustment of the gradients of tributaries so that they make accordant junctions (fig. 39) with the main valley—so "that none of them join the principal valley either on too high or too low a level" (69, p. 102).

Though exceptions to Playfair's law may be found, they are explicable in such a way as not to contradict the principle.

Many rivers, however, are guided, as will be shown below and in later chapters, by depressions in the land-surface due to earth-movements. Thus guided they proceed to erode valleys for themselves, and such a depression as a whole, after being modified in form by a river, is often termed the valley of the river. Such "valleys" are not wholly the work of rivers. Neighbouring mountain-masses also are not wholly residual—*i.e.*, do not owe their full height to the excavation of valleys around them by rivers. These, however, are the major landscape features; and smaller valleys, hills, ridges, and spurs may generally be regarded without any doubt as the work of erosion.

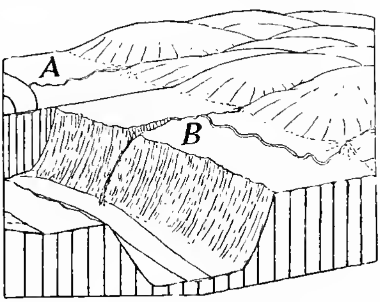


FIG. 39. — *A*, accordant junction of a tributary with a main stream. *B*, discordant junction.

In the latter half of the nineteenth century a corollary to Playfair's law gained acceptance (p. 2) — namely, that, if sufficient time is allowed, the slopes of valley-sides become more and more gentle, valley-floors become broader and broader, and the intervening ridges and spurs become lower and lower; and that, as the material of the land above sea-level is gradually carried away, particle by particle, the whole surface will be eventually reduced to very faint relief.

When the enormous age of the earth is taken into account, the fact that the land-surface is not a continuous plain sloping gently to sea-level seems at first to contradict the principle just stated; but the contradiction is only apparent. The explanation is that, from time to time, parts of the lithosphere have been uplifted, so that the work of erosion had to be begun afresh on them. Some parts of the earth's surface have been worn down almost to sea-level over and over again in the course of "geological time."

In the study of land-forms it is important to bear always in mind that no feature of the earth's surface is a finished product. The agencies which effect changes of form are everywhere at work:

every part of the surface is even now undergoing change, and its future forms will differ from the present as the present differ from the past.

"The flowing landscapes of geologic time may be likened to a kinetoscope panorama. The scenes transform from age to age, as from act to act; seas and plains and mountains follow and replace each other through time, as the traveller sees them replace each other in space. . . . Science demonstrates that mountains are transient forms, but the eye of man through all his lifetime sees no change, and his reason is appalled at the thought of duration so vast that the millenniums of written history have not recorded the shifting of even one of the fleeting views whose blendings make the moving picture" (Barrell).

The Cycle of Erosion.—In the study of land-forms it is convenient to picture the complete series of forms developed during the process of wearing-down of the land by erosion, as land-surfaces representing practically every stage occur. The period occupied by the whole series of changes in relief produced by erosion following uplift of a surface of any form above sea-level is called a *cycle of erosion*, or *geographical cycle*.* The surface upon which eroding agents begin to work is termed the *initial surface*; its relief is the *initial relief*. The surface of faint relief resulting from the prolonged action of normal erosion on a land-surface without interruption by uplift is termed a *peneplain*.

A vast lapse of time without relative movement of sea and land is necessary in order that a land-surface may be worn down to a peneplain, and if we were to judge by the evidences of recent movement of the land which are so abundant in New Zealand the conclusion would be inevitable that a cycle of erosion can never reach an advanced stage. New Zealand is, however, an exceptionally disturbed region, and, also, the immediate past has been a period of unusual instability of the whole lithosphere. Frequently, in the past, cycles of erosion have proceeded far enough to produce extensive peneplains.

A cycle is introduced by the uplift, relative to sea-level, of a portion of the lithosphere. It simplifies the elementary study of land-forms to regard this uplift as rapid. It is not to be regarded

* Davis, 4, pp. 249–78.

as ever sudden, or catastrophic, but it may take place so rapidly that the amount of erosion that goes on during uplift is negligible as compared with that which follows completion of the uplift. All uplifts are not so rapid as this, but the results produced by erosion will ultimately be very much the same whether the uplift is slow or rapid.

The initial surface thus uplifted may have previously been a land-surface, or it may have been part of the sea-floor. It may have been previously flat, or it may have had any conceivable kind of relief. The initial relief after uplift may be the former relief without modification, or it may be modified by inequality of uplift.

The uplifted mass may have any conceivable kind of geological structure. It may, for example, consist of massive rock, or, on the other hand, of stratified rocks with some of the strata more resistant to erosion then others, and these may be horizontal, tilted, or folded and faulted.

The amount of uplift (relative to sea-level) may be uniform throughout, as would be the case if a cycle were initiated by sinking of the ocean-level; or, on the other hand, uplift may be uneven.

The possible initial forms upon which erosion may begin to work to etch out *sequential* forms are thus many and varied, and it follows that the sequential forms produced during the course of the cycle are not always alike, but present an infinite variety. Allowance being made, however, for initial differences of form and structure, certain features are characteristic of the landscape in the various stages of the cycle of erosion—sufficiently so, indeed, to make such stages of great systematic value in classification and description.

The Cycle of Erosion in a Simple Case.—A theoretically simple case with which to begin the study of the cycle of erosion is that in which a previously flat or almost flat surface is uplifted to become the initial form. Consideration of the case in which moderate or strong relief of the land is inherited from a period anterior to the uplift introducing the cycle will, therefore, be reserved for a later chapter (Chapter XVII). A nearly flat initial surface might be a *plain of deposition* resulting from deposition of waste in flat layers or strata either beneath the sea or on land, where waste is spread by rivers, or it might be a plain or

peneplain which is the result of long-continued earlier erosion. The abundance of sedimentary rocks of marine origin now forming land makes it clear that the history of most land areas began with emergence of a former sea-bottom. In a great many cases uplift has been renewed later in such areas, perhaps more than once, so that the existing land-forms do not belong to the cycle of erosion initiated by that emergence; but clearly there must have been such a "first" cycle, the sequence of events in which can be deduced.

Uplift may be assumed to be slightly irregular, so that the initial surface is diversified by small initial inequalities and gentle slopes, the initial relief being just sufficient to give a definite

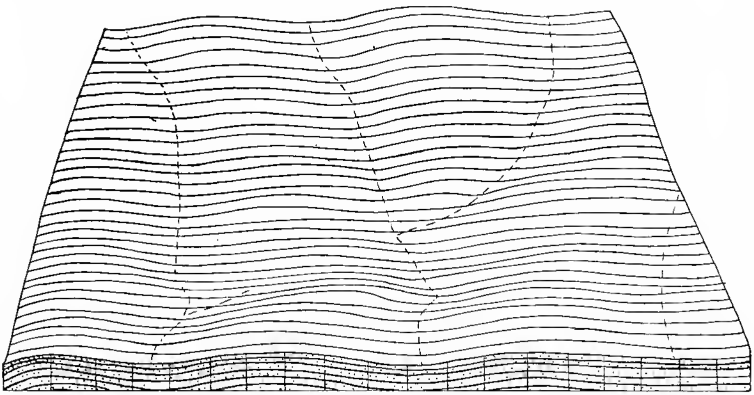
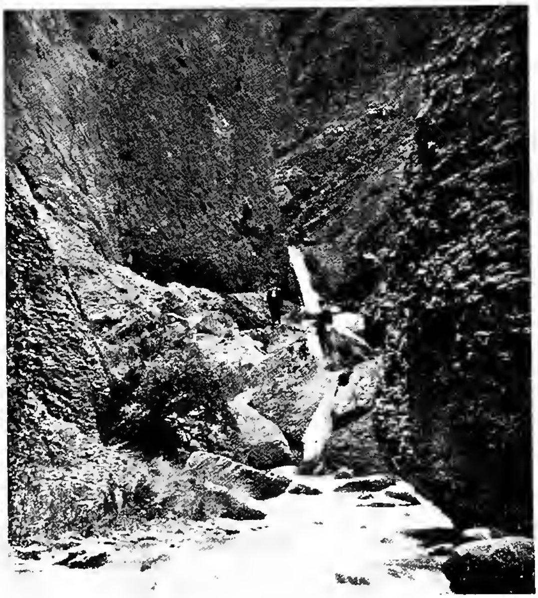


Fig. 40.—Diagram of an initial surface and consequent drainage.

direction to drainage (fig. 40). The strata immediately underlying the surface of a plain of deposition are warped during uplift to the same extent as the surface, to which they remain parallel. The topmost layer of sediment is in this case uniformly weak and unconsolidated, but some of the buried strata may be quite hard, and some are almost certain to be more resistant to erosion than the others. Moreover, there will be present, in any ordinary case, beneath the recently deposited formations older rocks with a more complex, perhaps intensely deformed, structure. These may not be deeply buried, and they will perhaps be quickly exposed by erosion.

Consequent Drainage.—When rain falls on the initial surface some of the run-off collects and flows along the initial hollows and wrinkles. Streams that have been guided thus by the initial slopes are termed *consequent*, their direction of flow being consequent upon the slope. The valleys which are soon cut by these streams, aided by the waste they pick up, are called *consequent valleys*, and the water-partings or divides between these are *consequent divides*, for their positions are likewise consequent upon the initial form of the



C. A. Cotton, photo.

FIG. 41.—Young valley being cut through limestone by a small stream, Broken River Basin, Canterbury, N.Z.

surface. Consequent river-systems and valley-systems thus come into existence.

Youth.—The *stage* of the cycle entered upon when the work of erosion begins on the uplifted surface is termed the stage of *youth*. Later stages are termed *maturity* and *old age*.

The characteristics of youth and of maturity in the rivers and their valleys, and in the surface as a whole, must be considered separately. The features of young valleys may be taken up first.

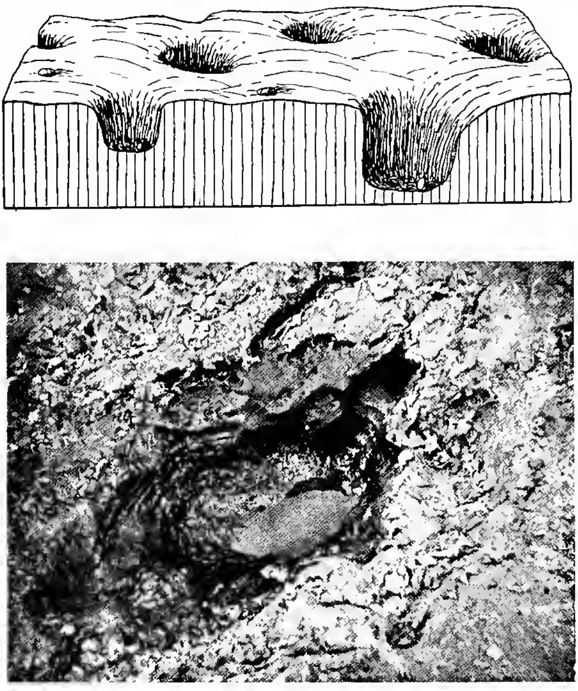
Characteristics of Young Valleys.—The young valleys which the streams are excavating in the stage of youth are generally narrow and steep-walled—mere trenches in the uplifted surface, the floors of which are covered from side to side by the streams during even moderate floods (fig. 41). There are generally rapids, and often falls, and sometimes lakes, along their courses. At first all the tributaries are, like the main streams, consequent, occupying subsidiary wrinkles or flowing down the side slopes of the larger hollows of the initial surface. Where the initial slopes are gentle these tributaries are not numerous. While they are young they do not necessarily join the main stream with accordant junctions, the tributary streams sometimes failing to deepen their valleys as rapidly as the main, so that the junctions remain discordant or "hanging." This feature is well seen in many New Zealand valleys, especially in Wellington and Marlborough districts. Here, however, the initial forms at the beginning of the present cycle were flat-floored valleys of an earlier land-surface (fig. 39, *A*), instead of an uplifted sea-bottom as in the theoretical case cited above. Where the underlying rocks are soft and the main streams are large and vigorous, as, for example, in the case of the Rangitikei and Awatere Rivers, the main streams have cut for themselves deep, steep-sided trenches. In their rate of downward cutting they have outstripped their small tributaries, which now cascade from mere notches high on the walls of the main trenches as in fig. 39, *B*.

All the above-mentioned features of young valleys, with the exception of lakes, result from the concentration of the erosive activity of young streams on downward corrasion. To begin with the consequent courses have quite uneven declivities, and these are generally so steep as to give the streams high velocities and power to transport a greater quantity of waste than is supplied to them. No waste, therefore, accumulates in the stream-beds. The bed-rock is exposed and rapidly worn down by the waste that is dragged over it by the current.

Potholes.—Where the supply of waste is limited, much of the deepening where hard rock is exposed in the stream-bed is due to the excavation of *potholes*—round vertical shafts, several feet across and with a depth often greater than their diameter (fig. 42)—which result where boulders or large pebbles are carried round and round for a long time by eddies. As the first boulders are worn away in

the process of grinding, others take their place, and so some well-rounded stones are generally to be found in each pothole.

Cañons.—The processes of stream corrasion just described, which cut vertically downward, would cut valleys of the same width throughout their depth—parallel-sided trenches, vertical-walled in the case of straight streams and sloping-walled in the case of



J. Wood, photo.

FIG. 42.—Above: Diagram of a stream-bed, showing potholes. Below: Pothole in the rock bed of the Wairua River, North Auckland, N.Z. (The river has been artificially diverted.)

curved streams (which, as explained in Chapter IX, cut sideways as well as downward). There are some young valleys cut in the tough limestone of Marlborough which serve as examples of this type of feature (fig. 43), while the inner valleys of large rivers, such as the Rangitikei, which have recently been rapidly deepened are

generally bordered by nearly vertical cliffs. Narrow trenches such as those shown in fig. 43 are not common in nature, however, for few rocks will stand for long as vertical or overhanging cliffs, and so young valleys are generally opened to a more or less acute V shape by slipping-down of material from the sides (figs. 44–48). As shown in fig. 44, the amount of material which thus slips into the stream and is eventually carried away by it is much greater than is the amount actually excavated by vertical corrasion; but it is the deepening of the channel that makes slipping-in from the banks possible.

B. C. Aston, photo.

FIG. 43.—Parallel-walled young gorge in tough limestone, a tributary of the Ure River, Marlborough, N.Z.

Falls and Rapids.—Initial irregularities in stream-gradients give rise to falls and rapids, but, unless there are very resistant rocks close to the surface, these tend quickly to disappear as the valleys are deepened. (Falls of this kind will be referred to again in Chapters XII and XXV.) Other falls and rapids—and these are somewhat longer-lived—are developed as the down-cutting streams encounter rocks of varying hardness (figs. 49, 50). Some rocks, such as unindurated mudstones, shales, sands, certain micaceous metamorphic rocks (schists), and much-jointed and shattered rocks in general yield very rapidly to stream corrasion. Others, such as

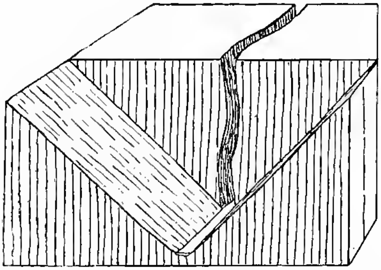
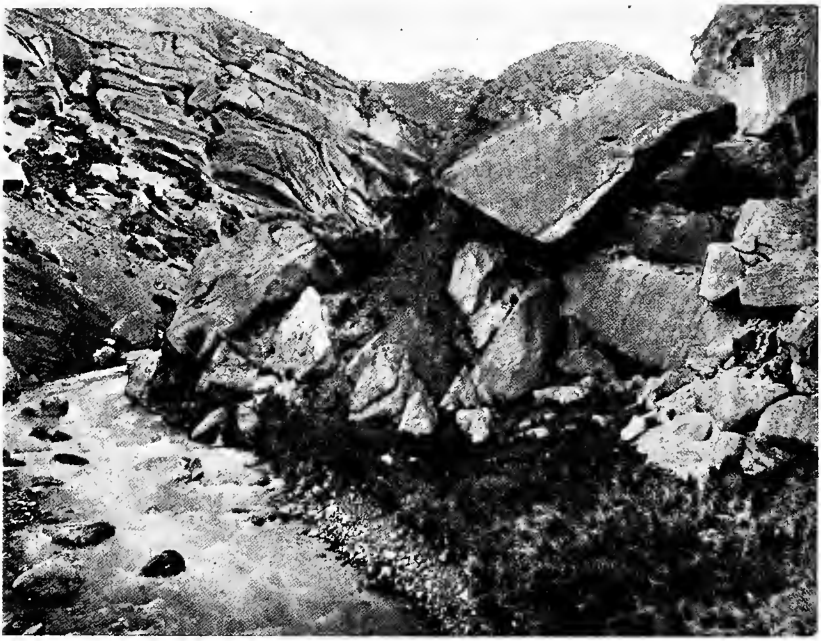


FIG. 44.—Diagram to compare the volume of material actually excavated by a down-cutting stream (rear block) with that of the material removed when down-cutting is accompanied by widening of the valley to a V shape (front block).

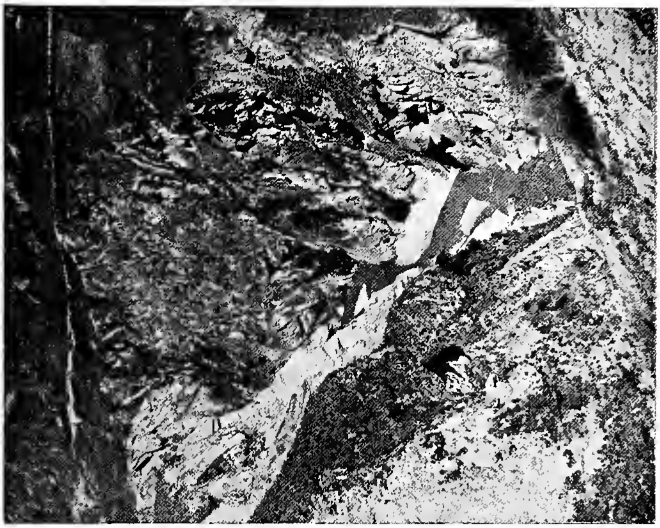
massive igneous rocks, gneisses, crystalline limestones, and unjointed indurated rocks in general, are worn away much more slowly. When, therefore, a down-cutting stream crosses a geological boundary from a resistant to a weak rock, the weak rock down-stream has the channel cut more deeply into it than the resistant rock up-stream, and at the boundary there is an abrupt steepening of the channel. At this point there will be a fall or rapid, according to the nature of the junction between the two kinds of rock.



R. Speight, photo

FIG. 45.—Fall of rock from the side of a young gorge, Porter River, Canterbury, N.Z.

Where the junction is vertical, or even slightly overhanging, rapids rather than distinct falls are generally formed (see fig. 51), because at the steep slope where the stream is leaving the resistant rock (after the channel has been more deeply excavated in the weaker rock below) the velocity is increased, and the stream thus has its capacity for corrasion enormously increased, with the result that the edge of the resistant rock is cut away much more quickly



C. A. Cotton, photo.

FIG. 47.—Narrow V-shaped valley, Shotover River, Otago, N.Z.

C. A. Cotton, photo.

FIG. 46.—Material slipping into a stream from the valley-side, Arrow River, Otago, N.Z.

C. A. Cotton, photo.

Fig. 48.—Widely-opened V-shaped young valley, Ngahauranga Stream, Wellington, N.Z.

F. G. Radcliffe, photo.

Fig. 49.—Huka Falls, Waikato River, N.Z., formed close to the edge of a layer of resistant rock exposed by the river cutting downward.

than the channel is deepened farther up-stream.* A steep slope in the stream-course, instead of an abrupt drop, is the result (fig. 51).

The chief fall-makers, as distinguished from rapid-makers, are horizontal or gently inclined beds of resistant rock, either lava-flows or resistant sedimentary strata, overlying weak rocks. The celebrated Falls of Niagara are a well-known example of falls developed on this kind of structure. Once the fall is established the weak material underlying the fall-making stratum is easily excavated by the splash and swirl of the descending water (fig. 52). As it is thus removed the edge of the fall-making layer overhangs,

F. G. Radcliffe, photo.

FIG. 50.—Aratiatia Rapids, Waikato River, N.Z., formed at the junction of a resistant lava rock (up-stream) and easily eroded pumice-beds (down-stream).

and from time to time blocks of it fall away, and the edge of the fall, being constantly renewed, is always fresh and sharp. A fall of this kind retreats rapidly up-stream, leaving a trench or cañon below the fall, the cross-profile of which is in strong contrast to that of the valley above the fall (figs. 53 and 54).

As a general rule the rate of retreat of such a fall is enormously rapid as compared with the rate at which the stream can cut

* "Erosion is most rapid where the slope is steepest" (Gilbert, 8, p. 102).

down through the hard stratum by vertical corrasion, and so the majority of cañons in horizontal strata with interbedded hard layers have been formed as falls retreated rapidly up-stream. The outcropping edges of the fall-making strata may be seen on the walls of the cañons below the falls. In New Zealand a number of falls in North Auckland—the Wairua, Whangarei, and Waitangi Falls, for example—have been formed as a result of the streams being compelled to flow over the surface of sheets of lava which have spread out and solidified in valley-bottoms.

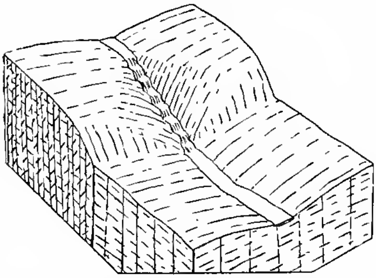


Fig. 51.—Diagram to illustrate the formation of a rapid at the junction of a resistant with a weak rock.

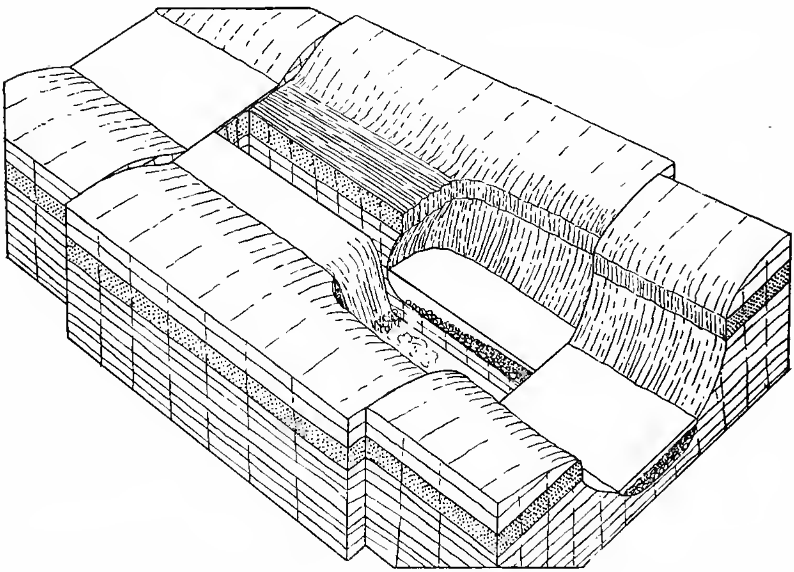
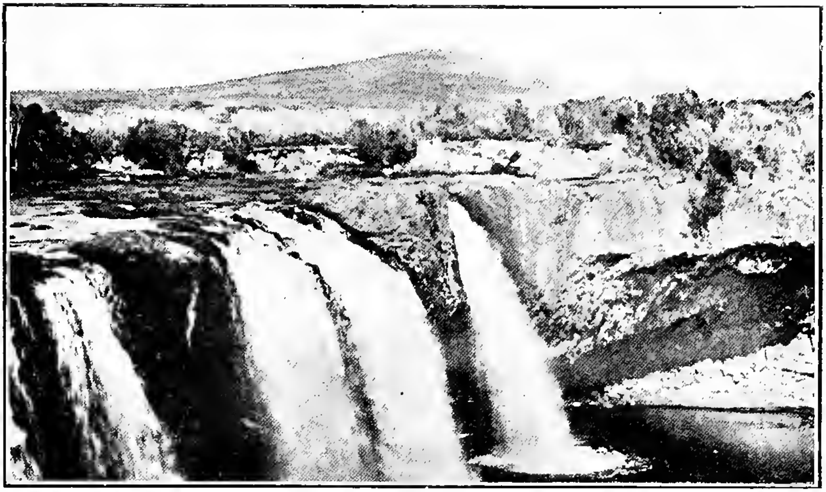
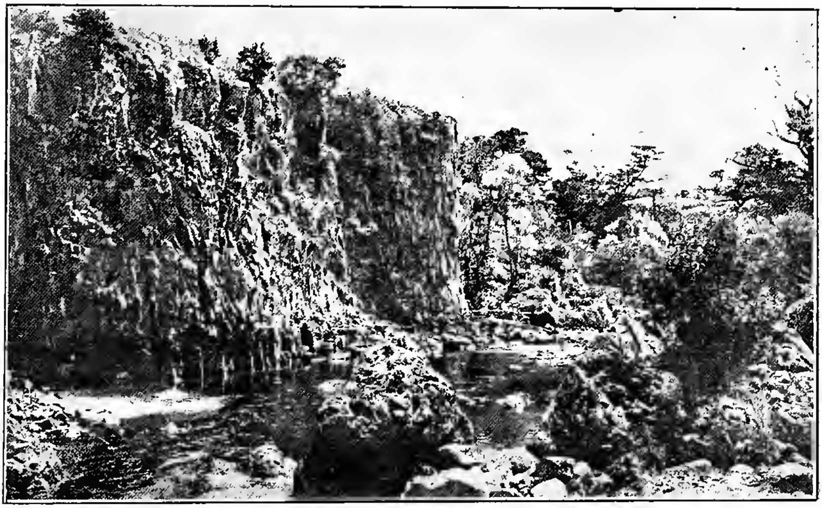


Fig. 52.—Diagram to illustrate the up-stream retreat of falls in horizontal strata. The central block is shown as though cut in two longitudinally, with the halves separated so that the profile at the edge of the fall may be seen; on the farther half the water above the fall is not shown. Note the development of the cañon below the fall.



C. A. Cotton, photo.

FIG. 53.—Wairua Falls, North Auckland, N.Z. Note the massive upper layer of rock overhanging the more jointed layer below.

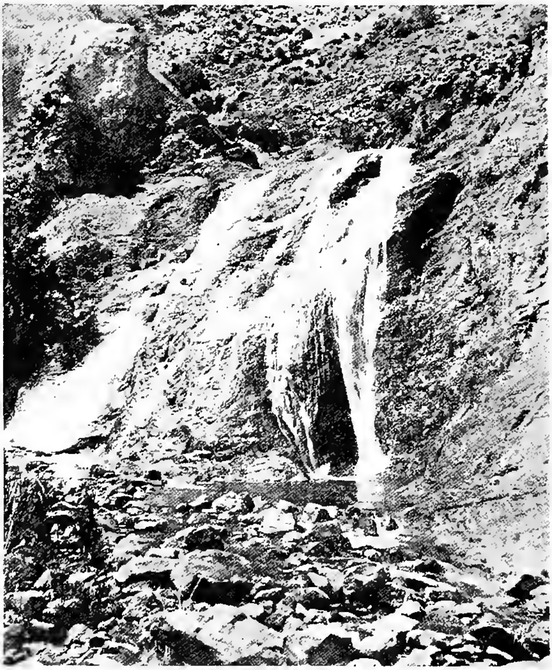


C. A. Cotton, photo.

FIG. 54.—The cañon below the Wairua Falls. Note the jointed rock at the base of the cliff.

The deeper part of the lava is more jointed, and thus weaker, than the superficial layer (figs. 53 and 54). The superficial layer of resistant rock is undermined and overhangs at the edge of the fall, and so the edge remains sharp as blocks fall away and the fall retreats.

Resistant inclined layers dipping at moderate angles up-stream form falls similar to those made by horizontal strata; but in this



C. A. Cotton, photo.

Fig. 55.—Cascade over the outcrop of a hard sandstone layer interbedded with mudstone strata, Clarence Valley, N.Z.

case the falls can be worn back only a short distance, as they diminish rapidly in height, soon giving place to short rapids and then disappearing. Resistant strata dipping down-stream form rapids rather than falls, unless the dip is very steep, in which case cascades will be formed (fig. 55), which are afterwards worn back into rapids.

Lakes.—Initially undrained hollows must occur on any irregularly uplifted surface. Water collects in such initial hollows and forms lakes, which are consequent on the initial form of the surface (fig. 56, *ce*). Generally lakes are transient features, and most of those that are consequent on the form of an irregularly uplifted surface disappear early in the cycle of erosion initiated by the uplift. This is true especially of lakes high above sea-level. In the steeper parts of the course of the consequent rivers (*ef*, fig. 56) formed by the overflow from lakes of this kind deep trenches (*egf*) are soon cut. The heads of such cañons work up-stream (from *e* to *d*) if the stream-gradients are steep, and so the outlet of a lake is cut down as a notch, and the lake-level is gradually lowered until the lake is drained off.

At the same time corrasion is proceeding along the stream or streams (*abc*) which supply water to a lake, at first in the steeper

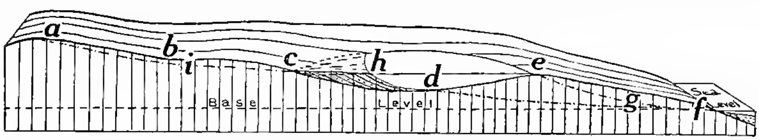


FIG. 56.—Diagram to illustrate the draining and filling-in of a consequent lake. Initial profile, *abcdef*; initial lake, *ce*.

parts of their courses and perhaps later throughout their whole length (*aic*). As a result the streams carry abundant waste, all the coarser and much of the finer part of which is dropped in the lake, for there the water loses its velocity and hence its transporting-power (fig. 56, *chd*, where the lake is represented as partly filled before lowering of the outlet begins). The water leaving a lake at its outlet is nearly always clear, having been, as it were, strained free of sediment. Abundant waste is thus deposited in the lake and built up above lake-level by the inflowing streams, and so the lake is reduced in size.

Lakes, whatever their origin, eventually suffer the same fate. Low-lying lakes may disappear as a result of filling only; but in most cases filling and lowering of the outlet go together. The size of most of the large lakes of New Zealand—*e.g.*, Wakatipu and Taupo—has clearly been reduced in both these ways. The Kawarau and Waikato Rivers, which drain these two lakes, leave them as crystal-clear streams, free from sediment.

CHAPTER VI.

THE NORMAL CYCLE (*continued*).

Base-level and grade. Maturity of rivers. Graded reaches. Dissection of the upland. Texture of dissection. Development of master streams. Coastal plains. Insequent streams. The law of equal declivities.

Base-level and Grade.—In the foregoing account of the activity of young streams it has been assumed that the streams flow initially at a considerable height above the sea, under which condition their average slopes and velocities are high and they cut downward energetically. There is, however, a sharp downward limit to active down-cutting. As a stream cuts down so as to approach *base-level* (an imaginary extension of sea-level under the land,* fig. 57) the rate of deepening rapidly decreases, for the level of the stream, though it approaches base-level, can never quite reach it except where it enters the sea. In order that the water of a river shall flow its surface must have a certain slope down to the mouth, which, in the case of rivers flowing into the sea, is at base-level (sea-level). Every part of the channel of the stream must therefore remain at such a height that there will be a slope sufficiently steep to carry off the water. The necessary slope is steeper for waste-laden water than it is for clear water.

The minimum necessary slope varies not only in different streams and at different times, but also in the same stream and at the same time with varying conditions, chief among which is distance from the mouth. The necessary slope becomes steeper with increasing distance from the mouth, chiefly because towards the source the quantity of water in the stream is less.†

* As defined by Davis, 4, pp. 381–412.

† "*Cæteris paribus*, declivity bears an inverse ratio to quantity of water" (Gilbert, 8, p. 114).

A stream that has attained the minimum slope under existing conditions is said to have reached *grade*, or to be *graded* (fig. 57). The longitudinal profile of a graded stream approximates to a parabolic curve. There are always, however, small departures from the ideal curve, and these are due largely to irregularity in the increase of stream-volume down-stream, this increase resulting in part from the junction of tributaries of various sizes at irregular intervals.

A factor that influences the steepness of the graded slope at any particular place and time is the amount of waste being supplied farther up-stream. This material has to be transported, and the fact that the profile is graded at any place implies that the supply of waste to the stream by tributaries and by rock-streams and soil-creep on valley-sides is exactly equal to the amount the stream can carry past that place. If the supply were greater the surplus would be deposited farther up-stream in the river-channel, which

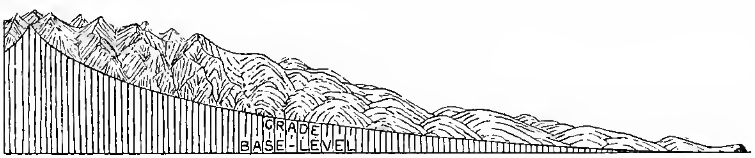


FIG. 57.—Longitudinal profile of a graded river, showing the relation of grade to base-level.

would thus be steepened, giving the flowing water progressively higher velocity and transporting-power until it was able to carry the whole of the waste supplied to it. If, on the other hand, the supply were less than the stream could dispose of, its bed would be swept clear of waste and it would farther deepen its channel, reducing the slope and so decreasing its own velocity and transporting-capacity. The graded condition, therefore, represents equilibrium between the amount of waste supplied and the transporting-capacity of the stream, and also between the processes of downward cutting and deposition in the stream-channel.

When, owing to excess of transporting-power over waste-supply, a stream cuts downward to establish or maintain grade, it is said to *degrade*; and the process is termed *degradation*. When, on the other hand, owing to excess of waste-supply over transporting-power, a stream deposits in and so builds up its channel to establish

or maintain grade, it is said to *aggrade;* and the process is termed *aggradation.*

In streams that are not yet graded degradation is rapid, as is shown by the cañon-like valleys of young streams. When grade is established downward cutting becomes infinitely slower, but does not altogether cease. Afterwards the slope of the graded profile will generally be reduced gradually in steepness, but only with extreme slowness, as the supply of waste falls off owing to the gradual reduction of the relief of the whole region.

Maturity of Rivers.—It is obvious that, when a river is graded, falls, rapids, and lakes, which are irregularities in the profile, have disappeared. The stage of youth is then at an end, and the establishment of grade marks the passage of a river from youth to *maturity,* the next stage of the cycle.

Rivers become graded and therefore mature earliest close to their mouths, where their volume is greatest; and the mature, graded

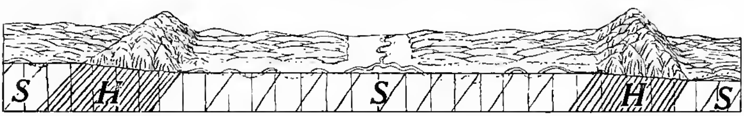


Fig. 58.—Diagram of graded reaches. The longitudinal valley-profile of a transverse stream crossing the outcrops of resistant (H) and weak strata (S) is shown by the front edge of the block. The river is graded on the weak but not on the resistant rocks.

valley extends gradually up-stream. The last statement is true only in a general way, however. It takes no account of differences in the hardness of the rocks over which the river flows.

Graded Reaches.—A river crossing the outcrops of alternating weak and resistant rocks will very early develop *graded reaches* across the outcrops of weak rocks, while the profile remains for a long time irregular and steep across the resistant rocks, where falls and rapids survive, as shown in fig. 58.

In the ideally simple case of streams eroding the gently warped strata underlying a newly emerged sea-floor such an alternation of weak and resistant rocks as is shown in fig. 58 could not occur, but where the initial form at the beginning of the cycle is an older land-surface this type of structure is not uncommon. It is conceivable, even, that it might be present beneath a thin layer of

newly spread sediment on a land newly emerged from the sea, in which case it would be quickly exposed by downward-cutting streams.

Graded reaches may be high above the *general*, or *permanent*, base-level, which is sea-level, but each is governed by a *local*, or *temporary*, base-level, which is the level of the first outcropping ledge of the next resistant rock down-stream. The wearing-away of this resistant rock takes place so slowly as to be practically negligible in comparison with the rate at which the adjacent weak rock can be degraded. Thus, though a temporary base-level of this kind is always being lowered, grade is maintained meanwhile across the weak rock next up-stream. In course of time grade is established across the resistant rocks also, the graded reaches are

C. A. Cotton, photo.

FIG. 59.—Graded reach in the Makara Stream, Wellington, N.Z.

joined together, and the stream becomes graded and mature for a great part of its length.

Dissection of the Upland. — The initial uplifted surface is in course of time all destroyed. The beginning of this process is seen in the early excavation of cañons. During the course of a cycle the surface as a whole, as distinguished from the river-channels, goes through stages of youth, maturity, and old age.

During the stage of youth the general outlines of the relief are determined by the form of the initial surface, which still survives in large or small areas on the *interfluves* (spaces between rivers). The actual sides of the young valleys of down-cutting streams are entirely the work of erosion in the new cycle, but while young

these valleys are narrow, and if they are some distance apart (*widely spaced*) they occupy only a part, perhaps a small proportion, of the total area. Consequent streams, including tributaries, are often not closely spaced, and in an early stage of the cycle streams of other kinds have not yet been formed. In a bird's-eye view, therefore, the newly cut ravines may scarcely be seen at all, and the initial surface may appear but little modified over large areas. In detail, however, the surface will now resemble more or less closely the dissected plateau of the Gouland Downs, shown in fig. 60, though

C. A. Cotton, photo.

Fig. 60.—Young stage of dissection. Gouland Downs plateau, north-west Nelson, N.Z.

in this particular instance the plateau is not really the initial surface, but a flat floor of resistant rock some small depth below it, from which some layers of very much weaker rock have been washed and dissolved away (Chapter XI).

The gradual etching of the land by the action of streams is termed *dissection*. While considerable areas remain undissected the surface is still in the stage of youth; but when dissection

is complete, the sloping sides of newly-cut valleys intersect one another to form well-defined divides, and no trace of the initial form remains the surface is *mature*. This holds true even though the dissecting streams have themselves reached the stage of maturity; while, on the other hand, a district may be maturely dissected by streams which are still young.

Plains uplifted bodily without deformation require a much longer time for their complete dissection than do districts of which the initial relief is diversified either on account of inheritance of relief from an earlier period of erosion or as a result of deformation accompanying uplift. In the case of diversified initial relief the

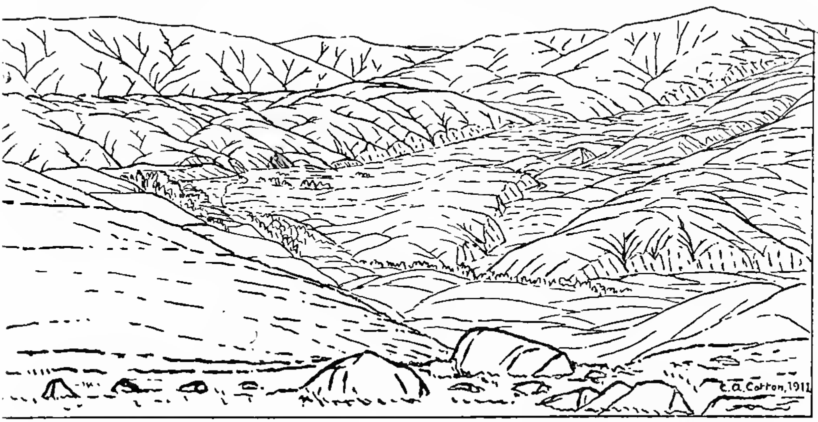


Fig. 61.—A maturely dissected surface; texture of dissection, fine. View northward from Kaukau Peak, Wellington, N.Z.

streams on the uplifted surface are numerous and closely spaced (as in fig. 61). Many of them may run at first down steep slopes, and such streams will at once begin the work of dissection. When all the closely spaced valleys are incised to some depth the sloping sides of adjacent valleys intersect and the surface is maturely dissected—that is to say, no remnants of the initial form survive on the interfluves. Such dissection takes place with extreme rapidity if the superficial material is unconsolidated (fig. 65). Hence parts of the former sea-floor that are strongly deformed as well as uplifted are practically unknown in the young stage. On a uniformly uplifted plain, on the other hand, most of the precipitation sinks

C. A. Cotton, photo.

Fig. 62.—Mature topography, Wellington, N.Z.; texture of dissection, fine.

C. A. Cotton, photo.

Fig. 63.—Mature topography, with coarse texture of dissection. North-east Valley and Mount Cargill, Dunedin, N.Z.

immediately into the ground, or gathers in pools to soak gradually away or to be dried up by evaporation; and any temporary streams formed on the horizontal surface as a result of unusually heavy showers are so sluggish that their corrading-power is negligible. Thus considerable areas of such surfaces may survive for a long time, even though built of soft material. The way in which they are eventually dissected is described below in the section headed "Coastal Plains."

Texture of Dissection. — Mature topography is of *coarse* or *fine texture* according as the stream-lines are widely or closely spaced (figs. 61–63). Close spacing is associated with impermeability, and wide spacing with permeability, of the underlying rocks.

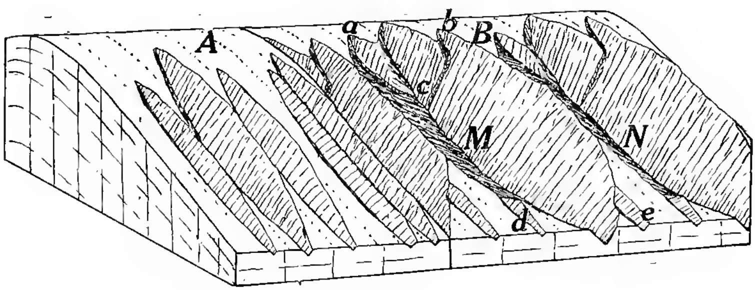
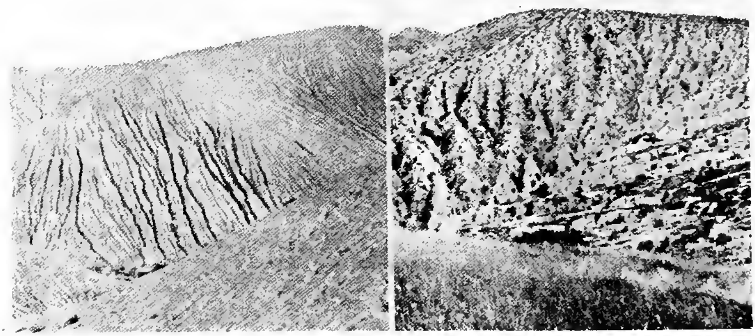


FIG. 64.—Diagram illustrating dissection by consequent streams and development of master streams.

Development of Master Streams. — On inclined surfaces the run-off is considerable, and there may be a large number of closely spaced consequent streams. These deepen their valleys side by side, and soon the initial surface on the portions of the interfluves separating the deepest (middle) parts of the young ravines are cut away, and the sides of adjacent ravines intersect, forming sharp ridges (fig. 64, block *A*). It is inevitable, if the streams cut deeply, that some of them, favoured by draining initially larger areas, by having slightly softer material to excavate, or by some other circumstance, cut their ravines more deeply than do their neighbours. These become *master streams* (*M*, *N*, fig. 64, block *B*), and as their ravines become deeper the sides are worn back until the ridges dividing them from the smaller, higher-level streams at either side are cut through, and the latter are compelled to run down into the

valleys of the master streams and become their tributaries. (Thus *ac* and *bc* join the master stream *M*.) A few master streams may soon receive practically the whole of the drainage of the surface, though, near the foot of the slope, where the master valleys are shallower and therefore narrower, diminutive beheaded remnants (*d*, *e*) of some or all of the other original consequent streams will still remain. This process, termed by Gilbert "abstraction" (8), has been termed also "the struggle for existence" among streams (Salisbury, 21).

The struggle for existence among streams is well illustrated on the mud-covered hill-slopes in the vicinity of Lake Rotomahana, New



a *b* *C. A. Cotton, photo.*

FIG. 65.—Consequent drainage and abstraction. View *a* shows an early stage in the development of master streams on the mud deposit from the Frying-pan Flat eruption of 1917, and view *b* a more advanced stage on the mud ejected from Lake Rotomahana in 1886. Both photographed in 1921.

Zealand, where showers of mud and fragments of pumice ejected from the basin of Lake Rotomahana by the volcanic explosion of 1886 and from Frying-pan Flat by that of 1917 formed a layer over the former topography, down the slopes of which innumerable consequent streams began at once to flow during every shower and to excavate ravines. Fig. 65, *a*, a view of the 1917 deposit, photographed in 1921, shows already a decided tendency for a few streams to gain the mastery; while fig. 65, *b*, a view of the 1886

deposit, also photographed in 1921, shows a much more advanced stage, in which a great reduction in the number of ravines has taken place owing to abstraction of the smaller streams by the masters.

Coastal Plains.—When a portion of the sea-floor emerges to become land, the uplifted portion is commonly a strip, narrow or broad, termed a *coastal plain*, bordering a pre-existing land (*old land*), which has been uplifted along with it. The uplift of a coastal plain may or may not be accompanied by deformation. A coastal plain of simple structure—that is, uplifted without notable

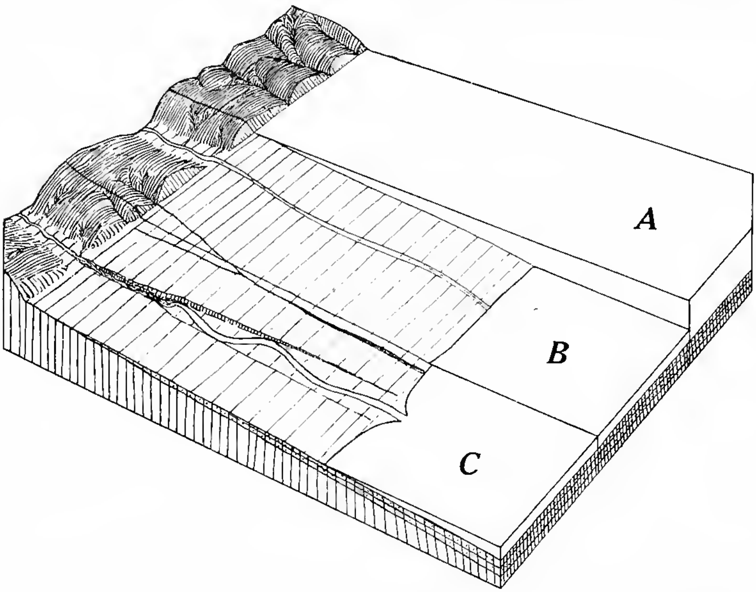


FIG. 66.—Diagram of a coastal plain of simple structure. Block *A* shows the old land before uplift, block *B* the newly emergent coastal plain, and block *C* the same after extended rivers have become graded in the soft coastal-plain sediments.

deformation, though perhaps gently tilted seaward—serves as an example in connection with which may be considered the dissection of a flat area with very little slope.

Such a coastal plain is shown diagrammatically in fig. 66. Block *B* shows the initial form exposed by withdrawal of the sea.

The majority of the rivers on a newly emerged coastal plain are the rivers of the old land extended across the newly uplifted sea-

floor and seeking the sea by the easiest (consequent) paths. These are *extended* rivers. In the simplest case their courses are straight, parallel with one another, and at right angles to the shore-line; but, obviously, even small irregularities of the initial surface will cause the rivers to take less direct courses, and two or more may

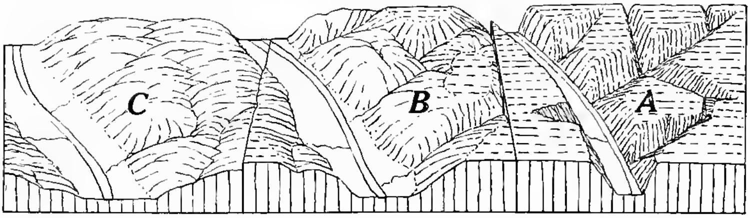


FIG. 67.—Diagram illustrating the dissection of an uplifted plain by insequent branching streams. *A*, young stage; *B*, dissection approaching maturity; *C*, mature stage.

unite before reaching the sea. These extended rivers, carrying as they do a considerable volume of water when they leave the old land, are competent to cut down and grade their courses quickly in the weak sedimentary rocks of the coastal plain. Broad areas of the flat interfluves may, however, long remain undissected.

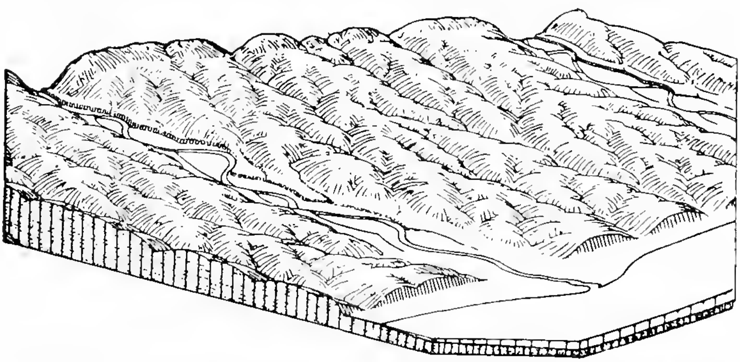


FIG. 68.—A coastal plain maturely dissected by extended consequent, new consequent, and insequent streams. (After Davis.)

In New Zealand there is a strip of coastal plain of simple structure bordering western Wellington and part of Taranaki to a width of several miles. It was exposed as a result of uplift of about 600 ft. (Morgan, 63), and initially extended farther seaward than it now does, for it is bordered at the margin by wave-cut

cliffs. It is still young, but is crossed by the deep, mature valleys of extended rivers. The broad belt of maturely or sub-maturely

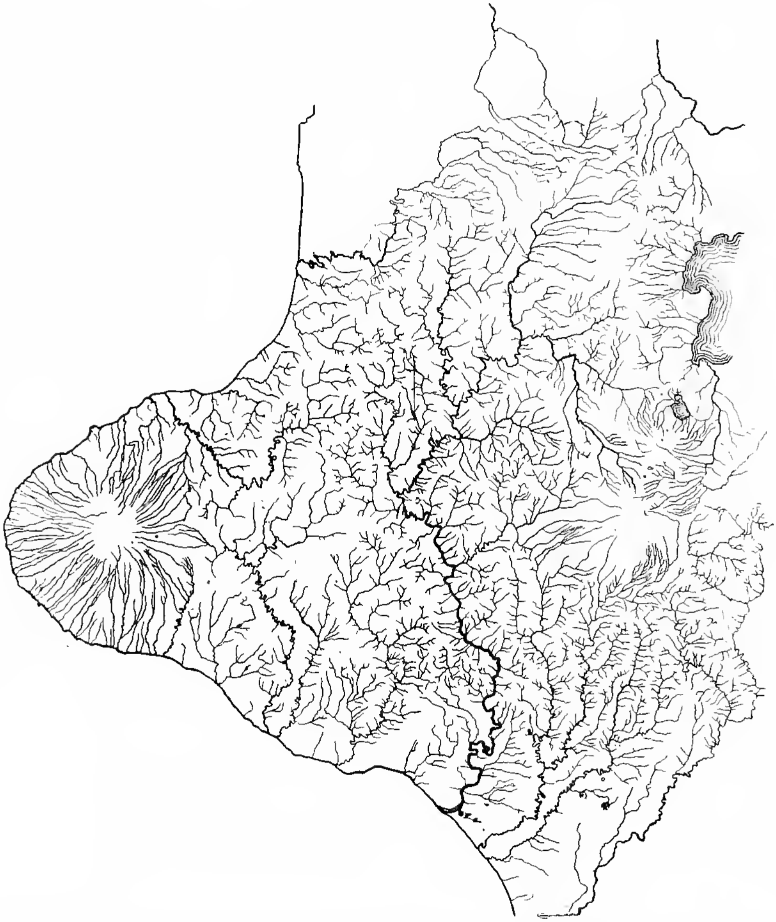


FIG. 69.—Insequent drainage pattern exhibited by the tributaries of the Wanganui and neighbouring rivers. Compare this with the pattern of radial consequent streams flowing down the slopes of the volcanoes Egmont and Ruapehu. (Map from Marshall's *Geology of New Zealand*.)

dissected weak rocks farther inland has also been described as a coastal plain, but, as the position of the old land relative to it

is not certainly known, it is best regarded simply as an uplifted portion of the sea-floor. The geomorphology of this area has not yet been worked out.

Small remnants of a few simple coastal plains are referred to in Chapters XXVII and XXIX.

Insequent Streams.—At a somewhat later stage new tributaries are developed. These start as steep ravines cut by concentrated rain-wash collecting in slight hollows accidentally formed in the steep sides of main valleys. As these gullies grow longer and deeper they receive an increasing amount of water both as surface run-off and as seepage through their steep banks. They rapidly eat their way back into the interfluves by *headward erosion*. Streams starting in this way, the positions and directions of which are purely accidental except in so far as they are determined by the slopes of the sides of the main valleys into which they flow, are termed *insequent* (figs. 67, 68). They in their turn develop insequent tributaries, which also work back headward into the interfluves, so that the area of the undissected surface is reduced with increasing rapidity.

The pattern, as seen on a map, which is developed by insequent drainage has been likened to the branching of an apple-tree, and has been termed *dendritic* (fig. 69).

The Law of Equal Declivities.—Where homogeneous rocks are maturely dissected by consequent and insequent streams, the side slopes of the valleys—that is to say, all the hillside slopes—tend to develop at the same angle, so that the ridges, spurs, and valleys become symmetrical. This is Gilbert's *law of equal declivities*. The law was stated by him as though the reduction of the slopes took place entirely as a result of stream-action, but it is true, nevertheless, as applied to the sum of the effects of the agencies soil-creep, &c., as is proved by the constant occurrence of symmetry in the land-forms. "In homogeneous material, and with equal quantities of water, the rate of erosion of two slopes depends upon their declivities. The steeper is degraded the faster. It is evident that when the two slopes are on opposite sides of a divide the more rapid wearing of the steeper carries the divide toward the side of the gentler. The action ceases and the divide becomes stationary only when the profile of the divide has been rendered symmetric" (8, p. 140).

CHAPTER VII.

THE NORMAL CYCLE (*continued*).

Development of subsequent drainage. Local base-levels. Shifting of divides Capture, or "river-piracy." Topographic changes following captnre. The Kaiwarra capture.

Development of Subsequent Drainage.—The nature of the rock, whether weak or resistant, is of great importance in determining the rate at which gullies can be extended headward by erosion. Where the rocks are all equally resistant insequent streams develop and branch impartially in all directions; but when a main stream crosses zones of alternately weak and resistant rocks tributary streams that begin to work back on the outcrops of weak rocks are enormously favoured thereby, and the development of new streams on the resistant rocks may take place so slowly in comparison as to be negligible. It is the tributaries which start on the weaker outcrops and are afterwards confined to and guided in the direction of their headward erosion by weaker zones of rock that are chiefly effective in dissecting the land-surface. Such streams are called *subsequent streams* (*S*, fig. 70), and the divides between them *subsequent divides*.

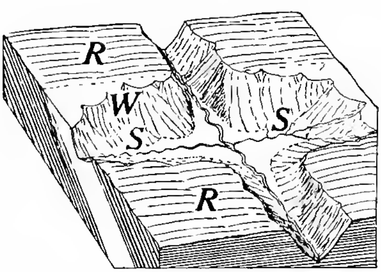


FIG. 70.—Diagram of the development of subsequent valleys. *R*, resistant formation; *W*, weak formation; *S*, subsequent streams.

Subsequent valleys that are guided by the outcrops of the weaker members of a series of stratified rocks (fig. 70) run parallel with the strike, and they are, therefore, longitudinal (see p. 7), or *strike*, valleys. The subsequent divides which separate them are

strike ridges. The subsequent longitudinal streams are generally developed as tributaries to transverse rivers, which are commonly, though not necessarily, of consequent origin.

Local Base-levels.—As explained in Chapter VI, the efforts of a young transverse stream to cut downward and attain grade are much impeded by the difficulty of cutting through the occasional strata of resistant rock that it crosses. By these the stream is literally "held up" for a relatively long period. Subsequent tributaries, which are eroded entirely along the outcrops of weak strata, have no such difficulties to contend with, and so they rapidly become graded (fig. 70), for the level of the main stream at the point of junction is for each side stream a local, or temporary, base-level (p. 63), which is being constantly lowered as long as the main stream below the junction is still degrading. In fact, the level of every point on a river may be regarded as a local base-level for the river above that point, with all its tributaries (Davis, 4, p. 400).

Shifting of Divides.—On the broad swells between the stream-lines on a plain uplifted with very slight deformation, where such is the form of the initial surface, the divides are very poorly defined; whereas by the time the surface has been dissected to the mature stage the divides have been reduced to lines or narrow strips and are very well defined. Such well-defined divides do not, however, remain always in the positions in which they were first determined by the intersection of the slopes of the neighbouring valleys. A very obvious *shifting* of a divide takes place where one stream is abstracted by another in the manner previously described (p. 68). Here a great portion of the valley-system of the abstracted stream is transferred in a moment to that of the master stream. This is an example of the sudden and radical transference of a divide from one position to another, which is termed *leaping* of the divide.

There is a much slower, and hence less spectacular, shifting, termed *creeping*, constantly in progress, from which no divide in a maturely dissected district is exempt. Wherever the heads of two streams are opposite to each other, one on each side of a more or less well-defined ridge, it is barely possible that the streams will degrade their channels at exactly the same rate, so that when the divide has been lowered to some extent by erosion it will be immediately beneath its former position. Usually one of the streams

will, on account of its greater steepness, its greater volume, or the weaker nature of the rock over which it flows, cut down more rapidly than the other, towards which the divide will be pushed. This is illustrated by fig. 71, in which possible differences in the resistance of the rocks are left out of account. The upper full line *ACB* represents the initial profile, and the lower full line *ACB* the

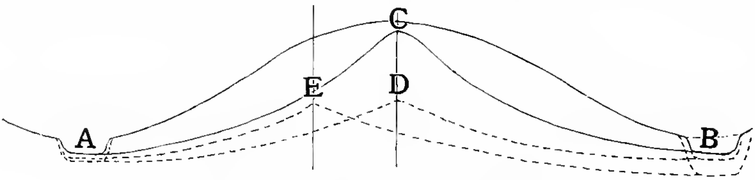


FIG. 71.—Profile of a shifting divide.

profile of the divide *C* after it has become sharply defined as a result of dissection by streams flowing as tributaries into the rivers *A* and *B*. As the surface is lowered, the divide may, at some later time, be at *D*, immediately below *C*; but it is much more likely to be at some point, such as *E*, to one side or the other of *C*. The shifting in this case might be brought about as a result of the more rapid deepening of the valley *B* than of *A*.

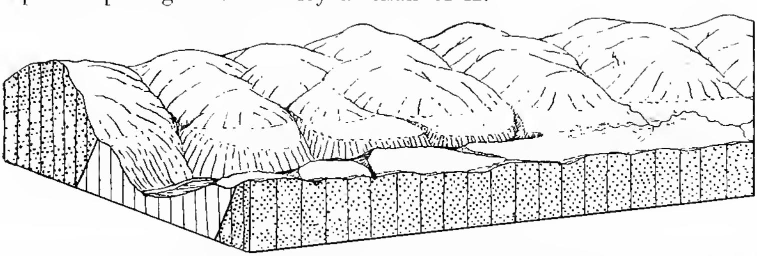


FIG. 72.—Diagram of a shifting divide in a subsequent depression. Remnants of the valley-bottom of the now shrunken stream on the right border the valley of the more vigorous stream on the left, which is rapidly pushing headward.

Shifting of this kind is most effective where the opposed streams are subsequents developed on the same weak formation (as in fig. 72), where proofs of rapid migration of the divide between their heads may sometimes be seen in the form of remnants of valley-floor deposits of the weaker stream, and portions of the valley-floor itself, remaining as terraces cut into by the

narrower and steeper valley of the more vigorous stream, which flows in the direction opposite to the slope of the terraces. The weaker stream, having been robbed of part of its valley-system, is of diminished volume. The valley-bottom near the divide will probably be swampy, as it is no longer occupied by the full-sized stream which eroded it.

An example of a shifting divide may be seen at Wellington, N.Z., at the top of the steep slope, drained by several streams, which lies between the city and Brooklyn. These small streams are rapidly pushing back the divide between them and the Happy Valley Stream, gravel-deposits of which lie on the divide and suggest that this stream had its head at one time far out over the site of the city.

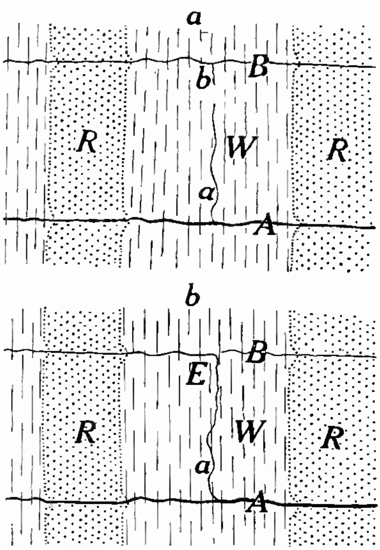


Fig. 73.—Diagrammatic maps illustrating the process of capture. *R*, outcrops of resistant rocks; *W*, of weak rocks. Map *a* represents the condition just before capture takes place; map *b*, just afterwards.

Capture, or "River-piracy."—In the early struggle for existence among consequent streams, in which a few streams assert their mastery in the manner already described, the headwaters of the minor streams which are abstracted and become tributaries to the master rivers may be said also to be *diverted*, or *captured*, and their diminished lower courses, if they survive at all, may be described as *beheaded*. *Diversion* of rivers into new courses takes place in various ways. Many diversions, producing drastic changes in river patterns, are effected by streams working headward under certain conditions so as to tap and lead off the water of others, as will now be described. To diversion of this type the term *capture*, or "river-piracy," is applied.

Other conditions being similar, the channels of large rivers are deepened more rapidly than those of their smaller neighbours; and

even when they are all graded the larger rivers flow in more gently sloping valleys than the smaller streams, and so at an equal distance from their mouths are more deeply incised. It frequently happens, therefore, that where two adjacent rivers cross the outcrop of a weak stratum, *W* (see fig. 73, *a*), the level of one, *A*, which is the local base-level for its tributaries, is considerably lower than that of the other, *B*. A subsequent tributary *a* of *A*, the more deeply entrenched river, working headward along the zone of weak rock, *W*, will, like all such streams, be graded for the greater part of its length, and may therefore be at a sufficiently low level at its head to tap the water of the higher-level transverse river *B*, which is led off to swell the volume of *A*.

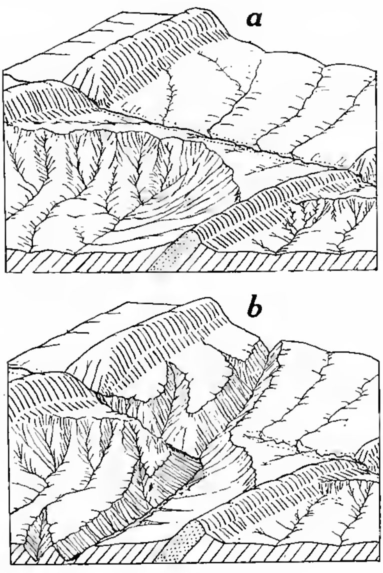


FIG. 74.—Diagrams illustrating capture of the headwaters of one transverse stream by the subsequent tributary of another. In the stage represented by diagram *a* capture is imminent; while in the stage represented by diagram *b* it has taken place. (After Davis, redrawn.)

The former upper course of *B*, which is now added to the valley-system of *A*, is said to have been *captured*, while *B*, which has lost its headwaters and is thus much reduced in volume, is said to have been *beheaded*. The stream *a* is termed the *diverter*. The bend, *E*, in the course of the captured stream where it turns from the captured portion of its valley into the valley of the capturing subsequent stream is termed the *elbow of capture*.

Generally, before capture takes place, the river *B* will have a subsequent tributary *b*, heading opposite to the stream *a*; but during the process of capture the divide between the heads of the streams *a* and *b* will slowly creep towards the river *B* until the last remnant of the stream *b* is eliminated and the divide formerly at the head of the stream *a* leaps to a new position across the former

course of the river *B*, the headwaters of which are transferred to the valley-system of the river *A*.

By the time the stage of imminent capture shown in fig. 74, *a*, is reached the headward erosion of the stream that is about to make the capture is hastened by an augmentation of its volume due to seepage of ground-water leaking down through the bed of the threatened river.

Topographic Changes following Capture.—Immediately following capture there are important changes in stream-profiles. The slope of the valley of the capturing stream, though graded, or nearly so, prior to the capture, is now much too steep, especially near the elbow of capture, for the largely increased volume of water it has to carry. Degradation at once becomes active, and the slope is reduced in steepness by the cutting of a trench. As this deepening steepens the slope down which the water from the captured stream flows, its valley also is correspondingly deepened. Thus the stream flows in a newly deepened trench around the elbow of capture. Tributary streams also become entrenched, on account of the lowering of the level of the main stream—their local base-level. As the depth of the trench around the elbow of capture increases, the new divide between the captured stream and the beheaded stream is pushed back so as to shorten the latter. It is probable, indeed, that by the growth of insequent tributaries from the newly deepened trenches, and by the general lowering of the land-surface on the weak rocks which follows the lowering of the local base-levels, the new head of the beheaded stream will be gradually transferred to the outcrop of the next resistant stratum down-stream. The former gorge, or water-gap, through this stratum is now no longer traversed by a stream, and becomes an "air-gap"

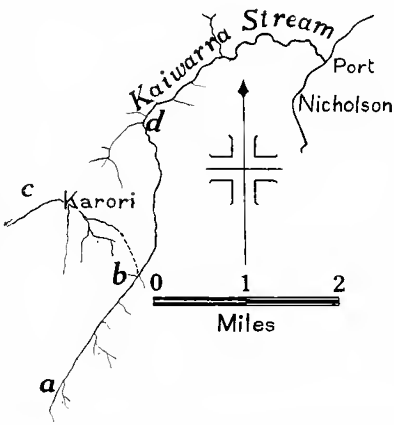


FIG. 75.—Map showing the Kaiwarra Stream. Capture has taken place at *b*.

(Chapter IX, fig. 122). When the floors of the adjacent valleys have been farther lowered by erosion an air-gap may be a mere notch in a subsequent ridge. In the early stages after capture the heads of the beheaded streams are poorly defined. Generally they rise in swampy flats which occupy parts of the floors of the valleys traversed by the streams before capture took place (Davis, 4, pp. 587–616).

Capturing streams, though usually subsequent, do not necessarily belong to that class, for insequent streams working their heads back under favourable conditions are also obviously capable of effecting captures. Nor is a sharp turn in the course of a stream necessarily associated with capture. Many sharp turns are con-

FIG. 76.—Sketch of the Kaiwarra capture. Captured stream (entrenched) on left; capturing stream on right; abandoned course through valley in centre.

sequent on the irregular form of the initial surface, and, as will be explained in Chapter XII, such irregularities are common in the courses of New Zealand rivers. In the Kaiwarra valley-system, near Wellington, there is, on the other hand, a very instructive example of stream-capture in which the capturing and captured streams are in the same straight line. It is described in the next section. The diversion of the present head of the Dry River (near Martinborough, N.Z.) from its former course as a branch of Blue Rock Creek affords a similar example.

The Kaiwarra Capture.—The capturing stream, a tributary or the head of the Kaiwarra, has effected the capture by working

back at first southward (from *d*, fig. 75), apparently as an insequent, and then south-westward as a subsequent along a belt of shattered and thus weakened rock (*shatter-belt*) on the line of a fault, until at *b* it has led off the head (*ab*) of a stream which formerly followed the course *bc* (as the head of the South Karori Stream). It would seem that the former course, *abc*, had originated by headward erosion of a stream at first insequent, *cb*, and then subsequent on the shatter-belt, *ba*. Fig. 76 is a sketch of this capture from a hill to the south-east, and fig. 77 is a photographic view from the

C. A. Cotton, photo.

Fig. 77.—View in the Kaiwarra valley, showing the abandoned valley of the beheaded stream, and the newly deepened valleys of the captured and the capturing stream, and (in the foreground) of a small tributary. (The lake in the main valley is artificially dammed.)

south. The captured stream is seen to be entrenched, and remnants of its former floor remain as a terrace, which is continued by the floor of the abandoned valley of the beheaded stream (in distance, left of centre-line, fig. 77).

In fig. 77 the entrenchment of a tributary of the captured stream is seen in the foreground.

CHAPTER VIII.

THE NORMAL CYCLE (*continued*).

Subsequent erosion on folded rocks. Adjustment to structure. The drainage of mountainous areas of folded rocks. Subsequent ridges in synclinal positions. Resequent drainage. Homoclinal ridges. Escarpments: their rapid retreat. Hogbacks. Cuestas. Mesas and buttes. Homoclinal shifting. Grading of slopes. Serrate and subdued topography. The effects of rock-solubility: erosion by underground water. Sinkholes and caves in limestone. Constructive action of lime-saturated water.

Subsequent Erosion on Folded Rocks.—In the preceding discussion of the development of subsequent streams it has been assumed that the strata are not steeply inclined. The structure may be homoclinal, and, when the surface has been worn down somewhat, the consequent rivers may cross the outcrops of the successive rock formations. This is the case in a coastal plain of simple structure, where the beds of sediment of which it is built dip gently in the same direction as the general slope of the surface, and so the consequent streams flow in the same direction as the strata dip, or at right angles to their strike.

In a district of closely folded strata, on the other hand, the larger of the consequent streams must follow courses corresponding to the axes of the synclines, for in these positions are the furrows of the initial surface (see fig. 78), and these streams are therefore longitudinal, or parallel to the general direction of the strike of the strata. The Jura Mountains, in Europe, are still drained mainly by longitudinal consequents of this type.

The larger consequents always have, however, consequent tributaries, which run, perhaps in minor transverse corrugations, down the flanks of the initial arches, and thus down the dip of the strata in the flanks of the anticlines. Such streams must degrade very rapidly, on account of the steepness of the slopes down which they flow. In their down-cutting they expose the outcrops of the weaker

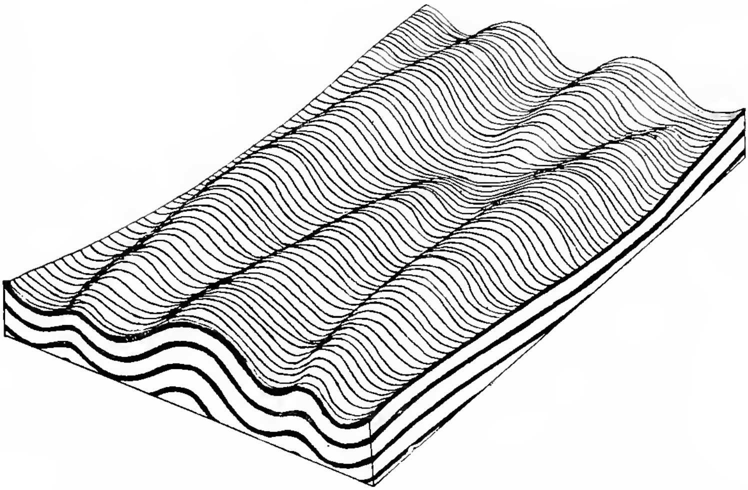


FIG 78.—An initial surface on folded rocks.

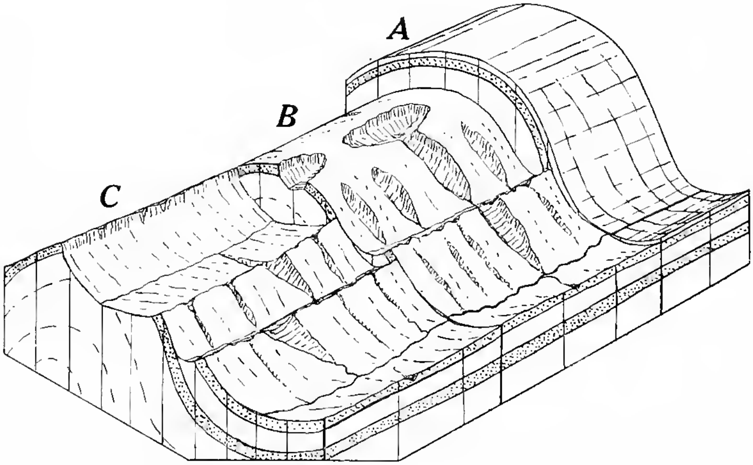


FIG. 79.—Diagram showing the development of subsequent drainage on folded rocks.

strata, and along these are developed other tributaries that are subsequent and longitudinal.

This process is shown in fig. 79, in which a portion of an arch and of a trough are represented. Two resistant layers of rock are shown stippled, while the weaker formations are left blank. The streams consequent on the initial form (block *A*) are a river following a longitudinal course in the trough and a number of small tributaries running down the flank of the arch. In the

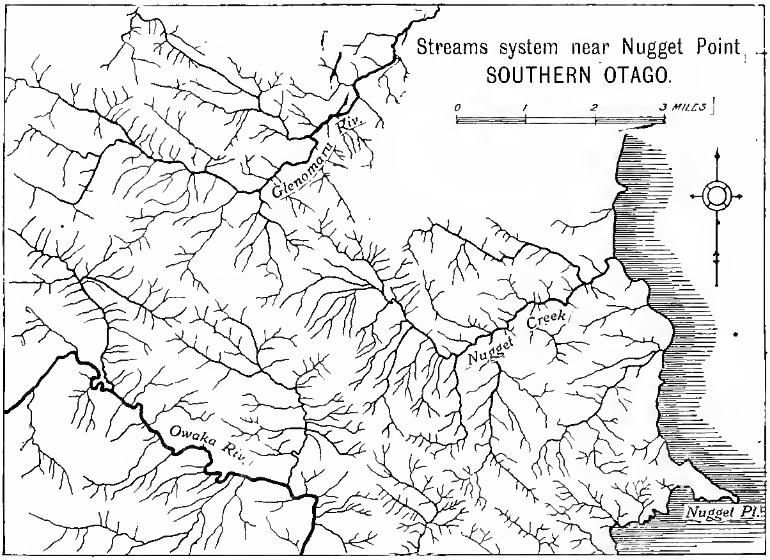


FIG. 80.—Map showing adjustment to structure near Nugget Point, Otago. There is a conspicuous development of subsequent ridges and valleys adjusted to the north-westerly strike of steeply dipping strata. (After Marshall.)

stage represented by block *B* the highest resistant formation has been cut through and a subsequent valley has been developed on the weak underlying stratum. Some streams have cut through the second resistant formation also. Block *C* represents a more complete development of subsequent drainage, when the outcrops of both the resistant strata form subsequent strike ridges.

Adjustment to Structure.—The development of subsequent drainage, going on as it does in all regions of stratified rocks whether gently or closely folded, causes streams of types other than

subsequent to shrink both in length and in volume, the subsequent streams meanwhile increasing in length and size as a result of headward erosion and the capture of earlier drainage. This general process, which results in the localization of stream-lines on weak zones, receives the name *adjustment to structure* (Davis). It begins in the stage of youth, but does not end with it: that is to say, adjustment is not completed, but is going on continuously as the stage of youth is left behind.

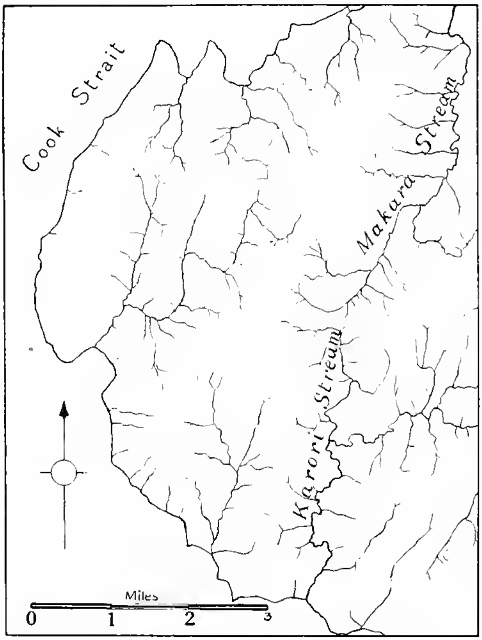


FIG. 81.—Map of the western part of the Wellington Peninsula, showing the alignment of the streams in a north-north-east and south-south-west direction, and an approach to a "trellised" pattern.

The drainage pattern that results appears, on the map, as a system of subparallel stream-lines following the strike of the rock-formations and joined up by occasional transverse portions, which cross the strike ridges in gorges developed as shown in fig. 79. The rectangular drainage pattern so produced is sometimes described as "trellised."

Some districts in the southern part of the South Island of New Zealand show a very thorough adjustment of streams to structure (see fig. 80), and the well-marked parallelism of the rivers in the hilly district about Wellington seems assignable to the same cause (see fig. 81).

Though the type of structure most favourable to the conspicuous development of subsequent drainage is an alternation of contrastingly weak and resistant rock-strata, adjustment to structure goes on in some measure practically everywhere. Even in massive rocks there

are almost always lines or zones of weakness, such as fault-lines, shatter-belts, and even master joints, capable of guiding the headward erosion of streams. Occasionally such structures as these have a definite arrangement or pattern which allows the drainage guided by them to be recognized as subsequent. The shatter-belt, for example, to which the whole of the captured and the head of the capturing portion of the Kaiwarra Stream (near Wellington) are adjusted (see p. 80) is conspicuous on account of its straightness and length, other streams besides the Kaiwarra being guided by it. It is also collinear with a prominent fault (see Chapter XII).

More often there is no such definite arrangement, and the drainage pattern on massive rocks must generally be described as insequent, not because it is known that there is no structural control, but because the structural control is not sufficiently systematic to be recognizable. This is the case even in some regions of sedimentary rocks where there are not notable differences in hardness between strata, as, for example, in many of the mountainous parts of New Zealand, where the drainage pattern is largely insequent, though among the larger streams consequents and subsequents may be suspected or even recognized with some approach to certainty.

The Drainage of Mountainous Areas of Folded Rocks. — In strongly folded and uplifted districts the land-surface as now found is generally far below the initial surface. In the early stages of the cycle introduced by the uplift with folding the great height above base-level, together with the steepness of the initial slopes, induces rapid erosion, and the streams have an excellent opportunity to seek out the weaker rocks and become adjusted to the structure. As the anticlinal ridges are initially high above the local base-levels and are flanked by steep slopes, their destruction goes on apace. Where they are formed of well-bedded rocks with weak layers along which, when the rocks are waterlogged, slipping may take place, the dip towards the valleys on either hand is conducive to the occurrence of landslips, which aid stream-action in destroying the initial arch.

Subsequent Ridges in Synclinal Positions.—It has often been the subject of remark, and even a source of wonder, that the rock-strata in some mountain-ridges form synclinal folds, and that valleys occupy the axes of the adjacent anticlines. It is some-

times implied that this is a general rule in mountain-ranges, and the explanation offered is that the rocks in symmetrical anticlines are stretched and broken and thus weakened during the process of folding, the rocks in the synclines being at the same time compressed and strengthened. If this were the case there would be a tendency towards the formation of subsequent valleys on the weakened rocks of the anticlines, between which would remain subsequent ridges on the strengthened rocks of the synclines. This hypothetical explanation is not necessary, however, for it is found that in the well-known and often-cited examples of synclinal mountains residual portions of resistant rock-strata overlying weaker

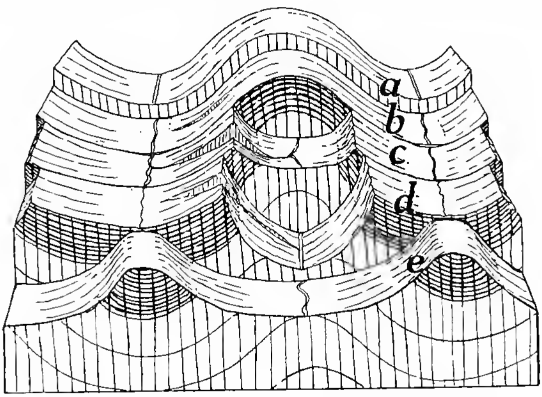


Fig. 82.—Diagram of the development of synclinal subsequent ridges.

strata form the ridges, while the other parts of the resistant strata, which must have been at a greater height than the present mountains, have been removed by erosion.

The development of synclinal subsequent ridges is illustrated in fig. 82, where *a* represents the initial form; *b* a very early stage of erosion, when a weak superficial layer of material has been removed, exposing a resistant stratum; and *c* a later stage, when the resistant stratum has been cut through by consequent streams and a subsequent valley has been developed on the weaker underlying rock in the axis of the anticline. The strip *d* shows a still later stage, at which the subsequent valley has been much

deepened; subsequent streams from now on receive most of the drainage, and the longitudinal consequents are dwindling. At the stage *e* widening of the subsequent valleys has gone on to such an extent that they are separated only by ridges localized on the remnants of the resistant stratum in the axes of the synclines. It is almost necessary to assume that a general uplift of the land occurs between stages *c* and *d* to account for the great deepening of the subsequent valley which takes place; but it is conceivable that this deepening might be due to some other cause.

The instability of initial arches that are not composed throughout of resistant materials is undoubted, but their very general non-survival is due rather to the fact that the great majority of rock-folds are quite ancient as compared with the rate at which relief is destroyed by erosion—so ancient that the valleys and ridges now observable belong generally to a cycle of erosion later than that introduced by the uplift that accompanied the folding, the surface having been at least once in the interim planed off more or less completely by erosion. This might have been shown in fig. 82 by introducing after strip *c* another showing a plain developed at a level a little below that of the valley-bottoms at stage *c*.

The majority of subsequent ridges in mountainous regions are not in synclinal positions, but mark the outcrops of homoclines of the more resistant strata (see p. 88); and it is important to recognize in this connection that stream-action is able, in the course of untold ages, to search out differences in the texture, the solubility, the closeness of jointing, and probably other properties of rock-masses which we are incapable of observing.

Resequent Drainage.—With deep erosion in folded rocks, perhaps after a vast thickness of material has been removed during and after a succession of uplifts, as the strata forming subsequent ridges in the earlier stages of erosion are removed, the folding of the deeper-seated rocks now exposed may still be parallel in a general way with that of the original surface. This is, of course, likely to be the case only in districts of open, symmetrical folding. Where this type of structure occurs it may happen that a folded resistant stratum has such a relation to base-level that, although at the beginning of the cycle there is a subsequent drainage pattern developed in an earlier period of erosion, as the rocks overlying the

resistant stratum are eroded away the streams migrate down the slopes of its surface into synclinal positions, and stripped, unbroken anticlines form the ridges between them (fig. 83, *A*). Synclinal valleys and anticlinal ridges simulating consequent features but developed from a subsequent drainage pattern are termed *resequent.* Similar valleys and ridges which had remained in consequent synclinal and anticlinal positions since their initiation would not be termed resequent, but would still be consequent even after the removal of a great thickness of rock (fig. 83, *B*).

In the mountains of Cape Colony, which are formed of very ancient folded rocks, and have been exposed to erosion for a vast period, anticlinal ridges and synclinal valleys occur for which a resequent origin has been suggested (Davis, 33).

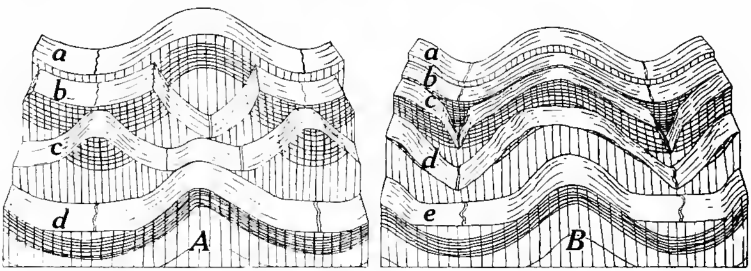


FIG. 83.—Diagrams contrasting resequent drainage, stage *d* in diagram *A*, developed from initial stage *a* through intermediate stages *b* and *c*, with consequent drainage, diagram *B*, persisting from initial stage *a* through successive stages *b*, *c*, *d*, and *e* during the removal of a great thickness of rocks.

Homoclinal Ridges.—By the time that an area of stratified rocks is maturely dissected by subsequent streams the ridges and uplands forming the divides between these have generally taken definite forms determined by the attitudes of the resistant formations. In general they are not symmetrical, for, owing to difference in resistance of the rocks on the two sides of the crest-line divide, the law of equal declivities is not in operation. Various types of feature are developed according as the strata dip steeply, at a moderate angle, or gently. Where the inclination is moderate to steep the outcrops of the resistant formations stand out as homoclinal ridges (figs. 84, 85). The back of such a ridge is a *dip slope* (figs. 86, 87), determined by the upper surface of the

C. A. Cotton, photo.

FIG. 84.—Homoclinal ridges, between the Ure and Clarence Valleys, Marlborough, N.Z.

C. A. Cotton, photo.

FIG. 85.—Steep homoclinal ridge (almost a hogback), formed of a thick bed of limestone, Clarence Valley, Marlborough, N.Z. The dip slope is towards the right, and the escarpment faces to the left.

C. A. Cotton, photo.

Fig. 86.—Dip slope (on right) of a homoclinal ridge in schist (metamorphic) rock, with steeper escarpment slope of the next ridge on left, Skippers' Creek, Otago, N.Z.

C. A. Cotton, photo.

Fig. 87.—Dip slope (seen in profile) determined by an inclined stratum of limestone, Ruakokopatuna Valley, Wairarapa, N.Z.

resistant rock only slightly lowered, and reduced in steepness, by erosion; while the front is an *escarpment* (figs. 85, 88), a steep slope, perhaps even a line of cliffs, which is *obsequent*—that is, faces in the direction opposite to the dip. As a general rule homoclinal ridges are unsymmetrical, the dip slope being less steep than the escarpment. When the dip of the rocks is so steep that the dip slope approaches the escarpment in steepness the homoclinal ridge is becoming a *hogback*.

Escarpments: their Rapid Retreat.—The condition necessary for the development of a true escarpment is the presence of a

C. A. Cotton, photo.

FIG. 88.—Escarpment of a homoclinal ridge, the Chalk Range, Marlborough, N.Z.

resistant stratum, inclined or horizontal, overlying conspicuously weaker rock, which wastes away rapidly, leaving the edge of the overlying stratum badly supported, so that blocks are constantly breaking away from a retreating sharp edge. This edge is analogous to that of a waterfall in rocks of similar structure, but extends throughout the length of outcrop characterized by this type of structure.

An escarpment is thus in rapid retreat, and this fact is generally made manifest by the presence of a sheet of coarse waste, sometimes thick enough to be a talus slope, derived from the edge of the resistant stratum and streaming down over the outcrop of the weaker rock below (figs. 92, 94).

C. A. Cotton, photo.

FIG. 89.—Serrate hogback ridge near Greenhills, Marlborough, N.Z. One of many passed on the road from Kaikoura to Upper Waiau.

C. A. Cotton, photo.

FIG. 90.—Hogback formed by a nearly vertical bed of sandstone, Maunsell's Taipo, east Wellington, N.Z.

Hogbacks.—Ridges formed on the outcrops of vertical or nearly vertical resistant strata are termed *hogbacks*. They are more or less symmetrical. While the cycle of erosion is not yet far advanced they have, in general, and especially when developed on the outcrops of thin beds of hard rock, ragged, irregular crest-lines, resulting from the intersection of the steep upper parts of concave side slopes (figs. 89, 90). The steep sides merge below with gentler slopes on the neighbouring weaker formations, which may be more or less covered with fallen blocks from the ridge, forming a talus slope. Hogbacks developed on the outcrops of strata that are not quite vertical are unsymmetrical, and the distinction between such unsymmetrical hogbacks and homoclinal ridges is not well defined.

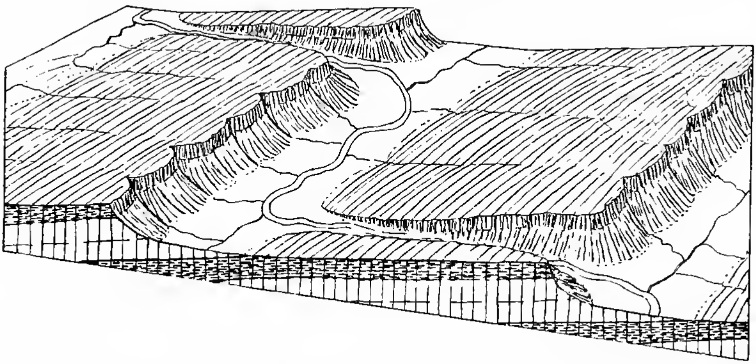


FIG. 91.—Diagram of cuestas separated by lowlands.

Cuestas.—In homoclinal ridges asymmetry becomes more pronounced as the dip of the beds diminishes; and when erosion lays bare the outcrop of a very gently dipping resistant formation the unsymmetrical upland which results is given another name—*cuesta** (Davis).

A cuesta naturally occupies a much larger area than does the ridge resulting from the baring of the outcrops of a more steeply dipping stratum. Its surface is a gently inclined dip slope which when followed downwards merges with the surface of the lowland developed on the overlying weak stratum, while upwards it is terminated by a sharp edge overlooking a steep escarpment (figs. 91, 92) leading down to a lowland developed on the underlying

* Pronounced *questa*.

weaker formation. Such a lowland between two cuestas, together with the dip slope bounding it on one side and the escarpment on the other, is sometimes termed a *vale*. Cuestas are common features of dissected coastal plains of simple structure, which are described as *belted* when alternating cuestas and subsequent lowlands have been developed on them. The dip slopes of such cuestas face towards the sea. In New Zealand, where the structure of even the youngest sedimentary rocks is generally somewhat complicated by folding and faulting, cuestas are common, and some have their escarpments towards the sea. This is the case in the Maungaraki Range and other escarpments in east Wellington.

A. C. Gifford, photo.

Fig. 92.—The escarpment of a cuesta, Oamaru, N.Z.

Varieties of cuesta-groupings, such as wide-spaced, close-set, and overlapping cuestas, depend on the thicknesses of the weak and resistant formations and the measure of the relief (Davis, 38, pp. 78–83).

Here and there most cuestas, and hogbacks and homoclinal ridges as well, are crossed by transverse streams in gorges, on the sides of which bare-rock outcrops occur and the dip and succession of the strata can be clearly seen (fig. 85).

Where cuestas are widely spaced, streams heading in their escarpments and joining as tributaries the subsequent streams in

the adjacent lowlands may be of considerable size. These streams (the direction of flow of which is obsequent—opposite to the dip) cut back vigorously at their heads into the cuesta, and somewhat deep embayments may thus be formed in the escarpment, so that it becomes decidedly sinuous instead of a straight line of cliffs. This is particularly the case when the relief has been so reduced by erosion that the cuestas are of small height as compared with their width (which is determined by the spacing of the subsequent streams, or the distance apart of the resistant strata).

Mesas and Buttes. — Features closely related structurally to cuestas and homoclinal ridges, though not developed in the same way by the headward erosion of subsequent streams, are formed

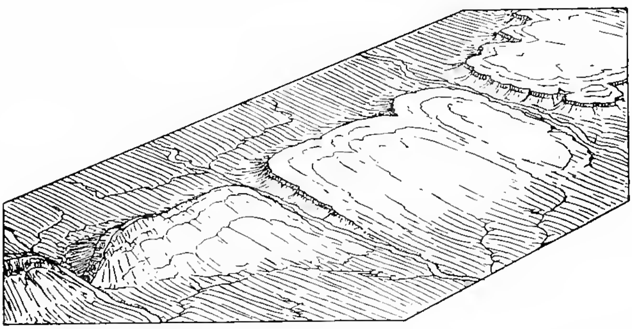


FIG. 93.—Diagram of the transition from a hogback (on the left), through a homoclinal ridge and a cuesta, to a mesa (on the right). (After Davis.)

by remnants of horizontal resistant strata capping weaker rocks. Large table-like forms are termed *mesas*, and small residuals are *buttes*.* The level top of a mesa or butte is the upper surface of the hard stratum but little lowered by erosion. The slopes on all sides are escarpments. The length and breadth of a butte are, at the most, not much greater than the height; while a mesa may be many square miles in extent, its surface forming a plateau. Fig. 93 shows the transition, with decreasing dip of the strata, from a hogback to a homoclinal ridge and cuesta, and then to a mesa.

* Pronounced *may-sa* and *bewt*.

Mesas are cut up by dissection and further reduced in size by the retreat of the escarpments by which they are bounded, for erosion on these is rapid owing to the steepenss of their slopes, a steepness which is maintained owing to the presence of the resistant capping formation. The way in which all escarpments retreat is essentially the same, and is described in the next section. Thus mesas are reduced in the course of time to buttes, and then finally disappear.

Mesas are particularly well developed where horizontal sheets of volcanic rock (originating as widely spread flows of very fluid lava)

C. A. Cotton, photo.

Fig. 94. — A rapidly retreating escarpment, Trelissick Basin, Canterbury, N.Z

lie over weaker material and the compound mass is in course of dissection by streams (figs. 331, 332, Chapter XXIV).

Some mesas are remnants of blocks of country differentially uplifted (Chapter XII) and formed of horizontal strata, the escarpments around which have retreated from the original boundaries of the blocks. This appears to be the origin of the table-topped mountains, such as Ngongotaha and Tarawera (fig. 327), in the Rotorua district, New Zealand, but it is not known to what extent these mountains have been reduced in size by the retreat of the escarpments forming their sides.

Differential depression of a block or syncline of a resistant stratum, on the other hand, may preserve it from destruction for so long that the general lowering of the land-surface may leave it standing out as a salient form; for such depression may lower the junction between the resistant capping rock and underlying weaker formations below local base-levels, so that undercutting and retreat of the edge of the resistant rock in the lowered block as an escarpment do not take place. Higher-standing surrounding areas of the resistant rock are meanwhile reduced by escarpment-retreat to smaller and smaller mesas, and finally disappear, and the weaker rocks below them are then rapidly lowered to small relief. Such is the explanation of the survival of Table Mountain, South Africa, suggested by Davis (33).

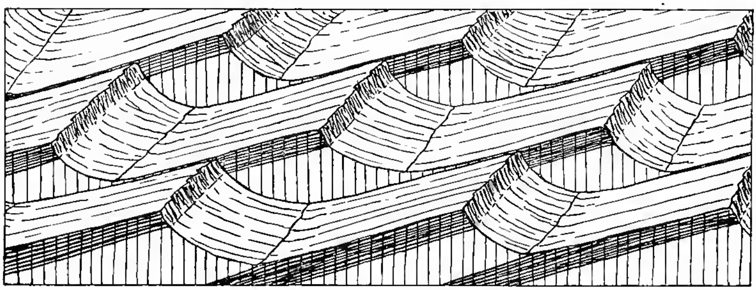


Fig. 95.—Diagram illustrating homoclinal shifting. Divides and streams are shifting to the left, down the dip. Three stages are shown, of which that in the front is the latest.

Homoclinal Shifting.—Because of the lack of homogeneity of structure in a cuesta or homoclinal ridge the law of equal declivities does not apply. Erosion is very slow on the gentle dip slope of resistant rock; but on the steeper obsequent slope, or escarpment, it is rapid (fig. 94). The divide formed by the crest-line of the cuesta or monoclinal ridge is thus forced to migrate towards the dip, and as the general level of the surface is lowered the subsequent streams and the valley lowlands migrate also in the same direction (fig. 95). The process is termed *homoclinal shifting.** Obviously the rapidity and extent of migration are greater in the case of gently inclined than in the case of steep strata.

* "Monoclinal" shifting of Gilbert (8, p. 140).

A striking effect of homoclinal shifting is seen where a stream crosses the strike diagonally (fig. 96). The stream may be straight at first (being possibly consequent), *A*, but by the time the surface is dissected into homoclinal ridges its course has become zigzag, *B*, as those parts of the stream which cross outcrops of weak rocks have migrated down the dip and now flow longitudinally. These are connected by transverse reaches crossing the outcrops of the resistant rocks by the shortest paths (Gilbert, 8, p. 136). Such zigzag courses are very common, and many have in all probability been developed thus, but a similar result might be attained under certain conditions by the joining-up of portions of successively captured transverse streams by subsequent reaches.

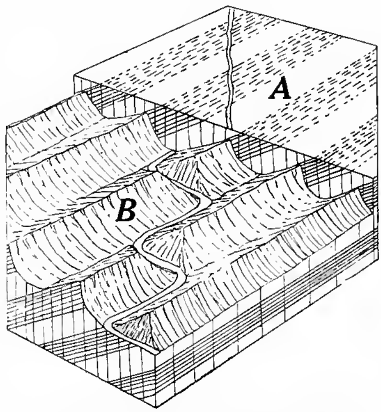


Fig. 96.—Diagram of the development of a zigzag course by homoclinal shifting.

Grading of Slopes.—On the sides of young valleys and gorges and in escarpments, where, owing to steepness of the slopes, removal of waste goes on as rapidly as the waste is produced by weathering, outcrops of bare rock occur, of jagged and irregular form, so that the slope is not only steep but uneven. Such slopes are analogous to the uneven profiles of young rivers, and, like them, they may be described as *ungraded* (see figs. 97, 98). Later, owing to cessation of down-cutting by streams, and to continued weathering and streaming-down of waste on the slopes, these are worn back to gentler gradients. During this process outcrops of bare rock, which at first are almost continuous, are gradually replaced by slopes of waste. These are at first short, discontinuous, and broken by rock-outcrops, but, as the outcrops are worn down, the waste-slopes become *graded* in a manner analogous to the grading of a water-stream, though the graded slope of a waste-stream is necessarily very much steeper than that of a water-stream on account of the relative immobility of the material of which it is composed. In this way are developed the smooth hill-slopes so prominent in the majority of familiar landscapes.

C. A. Cotton, photo.

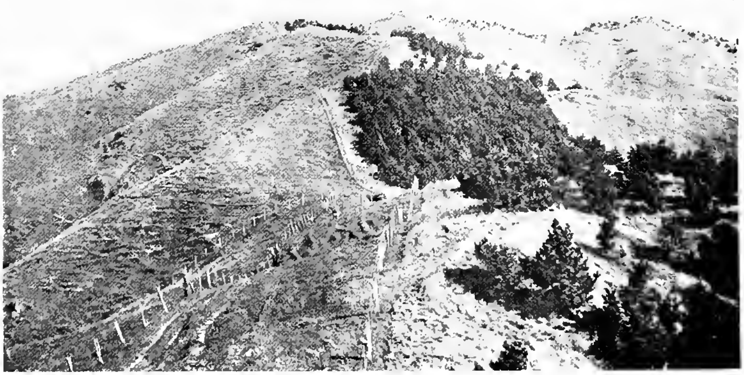
FIG. 97.—Ungraded valley-side, Dunstan Gorge of Clutha River, N.Z.

C. A. Cotton, photo.

FIG. 98.—Ungraded slopes, valley of the Dee Stream, Marlborough, N.Z.

C. A. Cotton, photo.

FIG. 99.—Part of the Kaikoura Range (Mount Tapuaenuku), N.Z., showing serrate summit topography and more rounded lower spurs.



C. A. Cotton, photo.

FIG. 100—The convex profile of a divide, Wellington, N.Z.

Serrate and Subdued Topography.—At the beginning of the stage of mature dissection the crest-lines of ridges and spurs are formed by the intersection of the slopes of valley-sides, which are, as a general rule, still steep, so that the ridges are sharp and uneven. The topography may be described as *serrate*. Later, however, they become rounded off, earliest in areas of moderate relief, and on the flanks and among the foothills of mountain-ranges, but eventually also among the mountain-peaks. This is a result partly of reduction of steepness due to the grading of land-slopes and of the headwaters of streams.

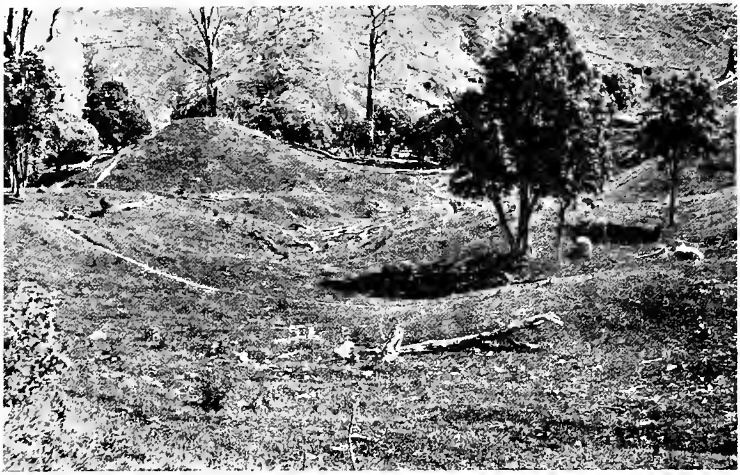
All the slopes produced by the rapid streaming of waste and by rain-wash may, however, be assumed, when approaching the graded condition, to be analogous in form to the graded profiles of water-streams, which are concave, and the intersections of concave slopes, however gentle they may be, are angular and unlike the broadly convex forms with which we are familiar on hill-tops (fig. 100). The convexity of the profiles of divides, which becomes prominent at this stage, is explained as the result of lowering of their surfaces by the unaided action of soil-creep. During the removal of a thin surface layer of uniform thickness from the crest of a ridge by this means the amount of material creeping past a given point increases progressively with the distance of the point from the divide. Hence for the removal of the layer by creep a slope increasing in steepness with distance from the divide is required.* Farther down the hillside stream-wash comes into play, and becomes increasingly more important in the removal of waste, and so there is a point of inversion between the upper convex and a lower concave graded slope.

When slopes have become moderately gentle in a district of coarse-textured dissection broadly rounded convex hills or mountains are produced, which are described as *subdued*. By the time that the stage of late maturity has been reached in the cycle of erosion of the land-surface most of the salient forms are subdued.

The Effects of Rock-solubility: Erosion by Underground Water.—Chemical weathering results in the removal of part of the waste in solution from all wasting surfaces. During the young and early-mature stages of the cycle of erosion mechanical erosion

---

* This explanation of the convexity of divides is due to Davis (see Gilbert, 47).



C. A. Cotton, photo.

FIG. 101.—Uneven slopes on limestone hillside resulting from underground drainage and solution, Ruakokopatuna Valley, Wairarapa, N.Z.

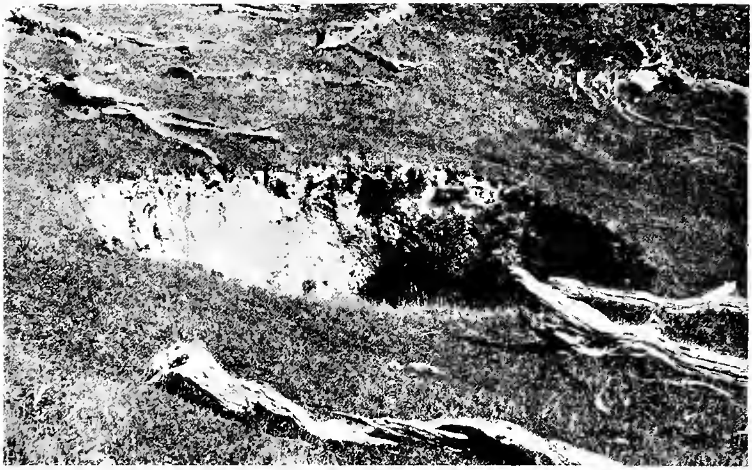
M. C. Gudex, photo.

FIG. 102.—Sinkholes in the Pareora district, South Canterbury, N.Z.

is so much more active on most rocks that it overshadows chemical erosion, and it is not until the stage of old age is reached, when mechanical erosion has become relatively feeble, that more than a negligible proportion of the lowering of the surface is due to this cause. In districts consisting largely of soluble rocks, such as limestone, however, the effects of solution are important in the earlier stages of the cycle also, and as long as the surface retains pronounced relief striking topographic effects are produced as a result of the enlargement of fissures by percolating water. Limestone and the closely related dolomite and magnesian limestone are the only soluble rocks that occur commonly in sufficiently large masses to allow solution to produce important topographic effects.

A general result of the enlargement of fissures by solution is a reduction of the run-off from the surface, as a great part of the precipitation sinks immediately into the ground and runs away into underground channels. When fissures are enlarged so as to form open passages they offer infinitely less resistance to the flow of water than do the minute passages in relatively insoluble rocks. There is thus far less heaping of water under elevations. In other words, the water-table is nearly horizontal, and is at a considerable depth beneath the surface, except at the bottoms of rather deep valleys, where the ground-water seeps out, or flows out as springs, to join permanent surface streams. Smaller surface streams are rare, and such as are present flow intermittently, being dry except after unusually heavy rains, and mechanical erosion may play a relatively small part in the lowering of the surface. A feature. therefore, of limestone regions is the coarse texture of the dissection, or, rather, the wide spacing of the stream-cut valleys, for minor irregularities due to solution may make the surface of the interfluves very uneven (fig. 101).

Sinkholes and Caves in Limestone.—There are certain features resulting directly from the formation of underground channels. Basin-shaped hollows (figs. 102, 103), sometimes of considerable size but sometimes only a few yards in diameter, may mark the upper ends of vertical solution-channels. These do not as a rule remain as open pits, but are choked by fallen blocks of rock and by finer waste washed in from the surface. The funnel-like hollows at the surface are termed *sinkholes*. The water that collects in them sinks down to join the underground water.



C. A. Cotton, photo.

FIG. 103.—Sinkhole, Ruakokopatuna Valley, Wairarapa, N.Z.

C. A. Cotton, photo.

FIG. 104.—Entrance of a cave in a limestone mesa, Gouland Downs, Nelson, N.Z.

Some sinkholes may be formed by the collapse of portions of the roofs of galleries dissolved out by water flowing along horizontal fissures. Such caverns are extremely common in limestone areas (fig. 104). Occasionally underground rivers flow in them (fig. 105), some of which are surface streams that take a short underground course and emerge again upon the surface. In other cases water no longer flows through the caverns, the streams that enlarged them having been led off to lower levels as neighbouring valleys have been deepened.

When enlargement of a cave by solution ceases, deposition of carbonate of lime begins on the roof and floor, the substance being brought in in solution by water percolating through the roof. Water can hold carbonate of lime in solution only when charged with dissolved carbon dioxide. A drop of the solution hanging from the roof evaporates slightly and loses some carbon dioxide. It can no longer hold the whole of its dissolved carbonate of lime, but deposits some as a tiny ring on the roof. Drop after drop hanging from the same point deposits layer after layer, so that the ring grows into a pendent tube which later becomes thickened by a deposit on the outside until it is a typical *stalactite.* The drops when they fall on the floor lose more carbon dioxide and deposit more carbonate of lime as a stool-shaped *stalagmite.* Thus stalactites and stalgamites are characteristic of limestone caves.

Caves formed by solution of limestone are common in various parts of New Zealand, and they generally contain stalactites and stalagmites (fig. 106).

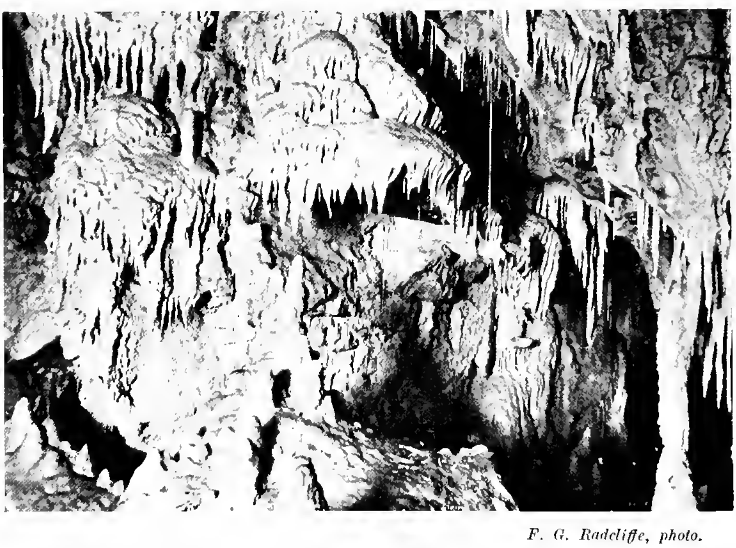
Where a spring emerges from an underground channel to form a full-sized surface stream, the valley of the latter, though perhaps deeply cut, is enclosed at the head by steep, perhaps precipitous, walls. It is termed a " blind " valley.

The greater part of the roof of an underground river-channel may fall in, leaving only a small arch, or *natural bridge.* A natural bridge may also be formed by a stream abandoning its course over a fall to flow along and enlarge a fissure so as to emerge below the former edge of the fall. Natural bridges are found in many of the limestone districts of New Zealand.

Owing to the prevalence of underground drainage, the continuous valleys characteristic of normally eroded regions may be replaced by series of closed basins connected by tunnels. Good examples

C. Beken, photo.

FIG. 105.—Stream flowing from a solution-tunnel in limestone, Broken River, N.Z. The mouth of the tunnel is being enlarged by exfoliation.



F. G. Radcliffe, photo.

FIG. 106.—Stalactites and stalagmites, Waitomo Caves, N.Z.

of such drainage may be seen on the Pikikiruna Range, between Riwaka and Takaka (fig. 107).

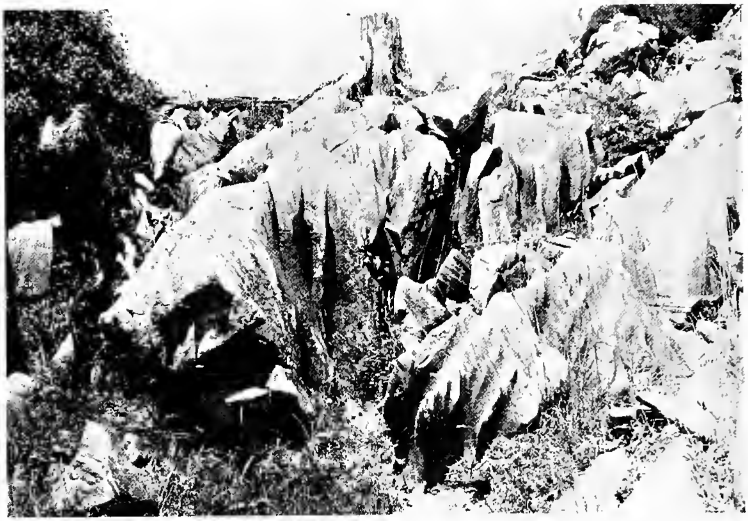
The residual soil is easily washed off a limestone surface when the natural vegetation is disturbed. Partly owing to loss of soil in this way, and partly to dryness at the surface due to the great depth to which the ground-water sinks, upland plateaux and mountains of limestone are generally desert regions. The naked surface of the limestone is often carved by the solvent action of rain-water into innumerable fluted pinnacles separated by deep and narrow trenches (fig. 108). Mesas and buttes of bare limestone that are

C. A. Cotton, photo.

Fig. 107.—One of a series of closed basins connected by tunnels to form a drainage-system, Pikikiruna Range, Nelson, N.Z.

rapidly wasting away and are carved into fantastic forms by the solvent action of rain occur at Waro, in the Whangarei district (figs. 19, 109). An architectural effect is given by differential solution along horizontal stratification planes.

Constructive Action of Lime-saturated Water.—Water that has become saturated with dissolved calcium carbonate when flowing in an underground course is ready to deposit some of this when it emerges at the surface and loses some carbon dioxide. In Dalmatia layers of crystalline calcium carbonate in the compact form of



C. A. Cotton, photo.

FIG. 108.—Limestone surface channelled and carved into fluted forms by rain, Pikikiruna Range, Nelson, N.Z.

C. A. Cotton, photo.

FIG. 109.—A limestone mesa, showing sculpture due to the solvent action of rain, Waro, Whangarei, N.Z.

travertine are deposited from solution in the beds of stream-channels where these have the form of cascades, thus causing falls to advance instead of conforming to the general rule that falls retreat.

In New Zealand the constructive effects of deposition of calcium carbonate are sometimes evident as mounds built at the mouths of springs which bring the substance to the surface in solution (fig. 110). The deposit is usually spongy in texture, with impressions of leaves and twigs around which it is deposited. This spongy deposit is known as *calcareous tufa*.

C. A. Cotton, photo.

Fig. 110.—Mound (in centre) of calcareous tufa deposited by a spring, Awatere Valley, N.Z

CHAPTER IX.

THE NORMAL CYCLE (*continued*).

The valleys of mature rivers. Lateral corrasion. Widening of valley-floors. Valley-plains and meanders. Planation. Cutting-off of meanders. Narrowed and cut-off spurs. Subsequent lowlands. Wide valley-plains. Underfit rivers.

The Valleys of Mature Rivers. — As a river becomes mature and graded farther and farther up-stream the cessation of rapid down-cutting is followed by a change in the cross-profile of the valley. The valley becomes more widely opened, for the sides slope back more and more gently as the interfluves are lowered, and at the same time the flat valley-bottom, or floor, increases in width. During the stage of youth down-cutting has kept ahead of the agencies which tend to reduce the steepness of the sides, so that these have succeeded only in opening the valley out to a somewhat acute V shape ; but in the mature stage, when deepening is practically at an end, these agencies continue their work, and the slopes become much more gentle, the angle between the arms of the V becoming very large.

The widening of the floor, which goes on at the same time, is due to cutting by the stream itself (*lateral corrasion*). Though a river is graded, and has therefore ceased to cut rapidly downward, it is not, as a rule, without energy. Where the current impinges against the valley-side the bank is attacked and cut back, and thus the floor is widened.

Lateral Corrasion.—In a perfectly straight stream the thread of fastest current would be in the centre, while at each side there would be almost still water fully loaded, or overloaded, with waste for the velocity at which it would flow, and incapable, therefore, of attacking the banks. There is no reason, however, to suppose that initial streams are ever perfectly straight, and if there is initial

curvature, however slight, a stream will itself enlarge its curves. In a stream with a slightly curved course (as shown by the fine dotted lines in fig. 111) the thread of fastest current is thrown always by the momentum of the stream against the concave bank, which is thus attacked and cut back (strips 2–5 and 2′–5′). In this way the curvature is increased while deepening of the valley is still in progress, for the stream cuts obliquely outward on its curves as well as downward. Thus by the time a valley is graded it is also somewhat winding (as defined by the broken lines in fig. 111), and its V-shaped cross-profile is unsymmetrical (strips 5 and 5′), the slopes (T, T') being steeper in the coves or amphitheatres against which the stream has cut (*undercut slopes*) than on the tapering and interlocking spurs running down to the convex banks. The slopes of the latter (S, S') are termed *slip-off slopes*, because of the way in which they are developed.

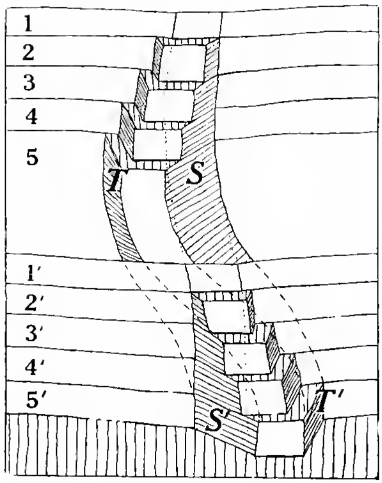
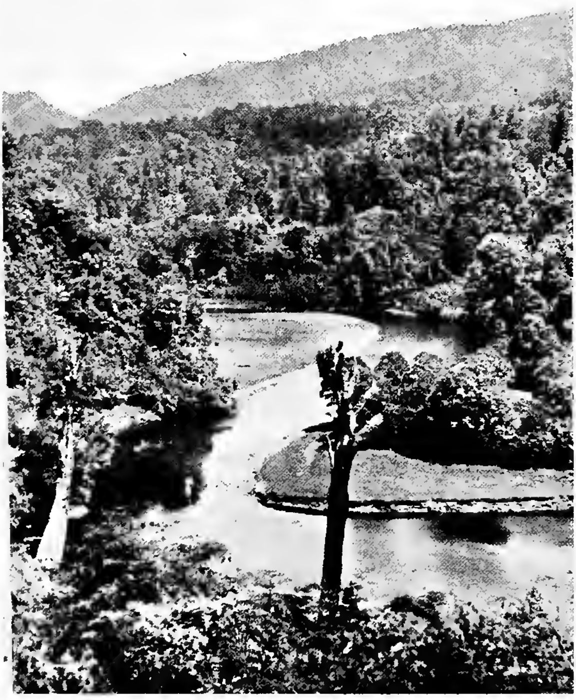


FIG. 111.—Diagram illustrating increasing curvature of a valley due to lateral corrasion accompanying downward cutting. Strips 1, 1′ show portions of the initial, slightly curved course; while strips 2–5 and 2′–5′ show progressive increase of curvature as the valley is deepened.

Widening of Valley-floors.—After a stream is graded, enlargement of the curves still goes on, but, since lateral cutting is not now accompanied by vertical cutting, further enlargement of the curves results in widening of the valley-floor. As the stream does not require the full width of the enlarged floor for its channel, it concentrates itself against the outer, or concave, banks of its winding valley, and deposits the coarser parts of its load along the inner, or convex, banks, forming flat areas of new land, which are covered only at times of flood. These are the beginnings of a

flood-plain. As they are at first a series of short, crescent-shaped, but slightly sinuous strips, they are at that stage, termed *flood-plain scrolls* (see fig. 112, and fig. 113, stage 2).

Deposition of coarse alluvium* (gravel or sand) along the convex bank results in part from the sluggishness along that side of the curved stream. There are, however, also cross-currents to be taken



G. Bourne, photo.

FIG. 112.—An early stage of flood-plain development, "flood-plain scrolls," Waimana River, Urewera country, N.Z.

into account, an upper one of relatively clear water, not fully loaded with waste, moving towards the outer (concave) bank, where it increases the cutting-power of the stream, and a return current

* *Alluvium* is the material of *alluvial* deposits—*i.e.*, deposits of sediment laid down by rivers.

along the bottom towards the inner (convex) bank (J. Thomson, 78). This bottom water is laden with waste, much of which it drops in the sluggish water as it approaches the bank. The actual movement of the water at any point is the resultant of the down-stream and cross-stream currents, as shown in fig. 113, stage 1, where the full arrows indicate the directions of currents in the upper layers of water and the dotted arrows those of the currents along the bottom.

The stream cuts not only outward on curves, but also down-valley, being carried in that direction by an accelerating force due to the general slope. It thus cuts into the interlocking spurs from the up-valley side, at first *sharpening** them (fig. 113, stage 2), then *blunting** them (fig. 113, stage 3), and eventually *trimming**

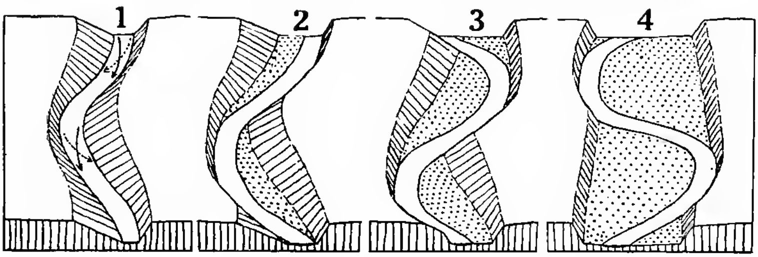


FIG. 113.—Diagram of widening of a valley-floor. Stage 1, part of the course of a stream in which slight initial curvature has been increased during down-cutting; stages 2, 3, and 4, effects of lateral corrasion after down-cutting has ceased—sharpening, blunting, and trimming of spurs, and development of a flood-plain.

them away altogether (fig. 113, stage 4). At this stage the sides of the valley are lines of rather steep bluffs, and the floor is flat, the flood-plain being by this time continuous except where interrupted by the actual channel of the river.

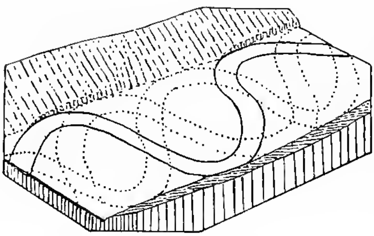
Valley-plains and Meanders. — A continuous flood-plain is sometimes termed a *valley-plain*. During every flood the surface of such a plain has a layer of fine waste deposited on it, owing to the checking of the current by friction when the water is spread out over the plain in a thin sheet, the main flow of the stream taking place still (and with a velocity greater than usual) along the regular channel. It is the deposit of mud spread in this way that

* Term introduced in this connection by Davis.

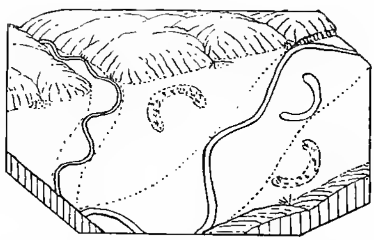
gives valley-plains their fertility. The land is, as it were, top-dressed by every flood.

The development of curvature in the stream-channel tends eventually towards the production of regular, flowing curves (termed *meanders*) which are of a size proportioned to the energy —that is, to the volume and velocity of the stream (Davis, 5 and 37). By the time valley-side spurs have been trimmed back and the flood-plain has become continuous the curves of a river have generally developed into symmetrical meanders.

Planation.—Widening of valleys as a result of lateral cutting or *planation* by streams does not cease when the originally interlocking spurs have been trimmed off, but continues while the hill-slopes are being graded and their steepness is being reduced. Let it be assumed that the flat floor bounded by simple lines tangent to the



114



115

Fig. 114.—Diagram showing the down-valley migration of meanders and the widening of the valley-floor by removal of successive strips where the stream undercuts the valley-sides. Direction of stream-flow and migration of meanders, right to left.

Fig. 115.—Diagram of a valley much widened by planation. The valley-plain is now much wider than the meander-belt (indicated by the dotted lines). Main stream flows from right to left.

convex curves of the stream is just wide enough to allow these curves to be developed into symmetrical meanders of full size corresponding to the size of the stream. The tendency of the curves to shift down-stream is no longer checked by barriers of solid rock. Having only the loose alluvium of the flood-plain to corrade, they sweep bodily down the valley, rebuilding the flood-plain behind them as they go (fig. 114.) This down-valley migration of meanders is quite rapid, and makes rivers unsuitable for geographical or farm boundaries. Old and new maps of the same river-valley will show

the meanders in quite different positions and of quite different shapes. The stream is still active in enlarging the radius of its curves, and so these are pressed outward against the valley-sides, which are eroded, a narrow strip of new flood-plain being added to the valley-floor by each meander as it travels down the valley. The foot of the slope of the valley-side is cut away in this process, leaving at first a low cliff, which is smoothed out to some extent by the grading agencies at work on the slope after the meander has passed by, the whole valley-side slope retreating slightly each time this occurs (fig. 114).

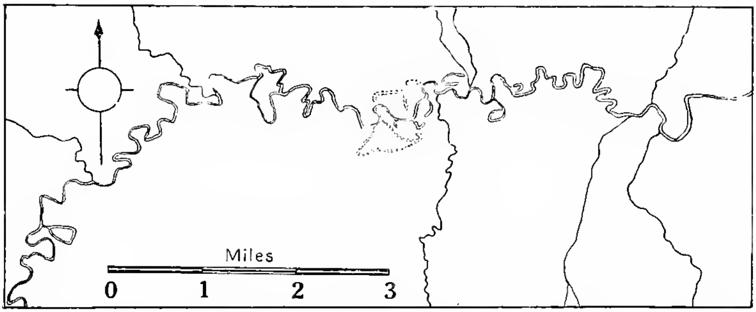


FIG. 116.—Map showing meanders and cut-off meanders in the course of the Taieri River through the Upper Taieri Plain, N.Z. (From maps by the N.Z. Department of Lands.)

Cutting-off of Meanders.—When meanders approach the maximum size appropriate to the size of the stream—small in small streams, large in large rivers—their outward cutting and enlargement still continues, but, as the curves are now S-shaped ("dovetail" meanders of Davis), the concave banks of adjacent meanders on the same side of the meander-belt approach each other and ultimately intersect. As the water in the down-valley meander is at a lower level than that in its up-valley neighbour, when intersection of the curves results in the cutting-away of the neck of flood-plain between them the stream takes a new course across the intersection. (Or, without actual intersection of the banks, at time of flood the stream may break across and scour out a channel through the narrow neck between adjacent meanders.) The former roundabout course, which is a meander towards the opposite side

of the valley, is abandoned or *cut off*. It is in this way that the size of meanders is limited. Those that have overgrown the maximum size set by the volume and gradient of the stream are cut off, and a portion of the stream-course is for a time relatively straight; but the development of new meanders begins at once. *Cut-off meanders* are common features of valley-plains (figs. 115, 116). At first they form horseshoe-shaped, or *ox-bow,*

C. A. Cotton, photo.

FIG. 117.—Narrowed spur in the Ngahauranga Valley, Wellington, N.Z

lakes or ponds, which later become swamps owing to accummulation of silt and growth of vegetation.

Narrowed and Cut-off Spurs. — Even while streams are still cutting vigorously downward—that is, before even the beginnings of a flood-plain have been formed—the development of curvature may lead to the narrowing and finally to the cutting-off of the spurs between adjacent curves in a way analogous to the cutting-off of meanders on a flood-plain. This takes place in small streams

which are compelled to cut deeply to attain grade. In these the limiting size of curves is small compared with the depth of the incised valley. As adjacent curves approach each other the crest-line of the spur between them is lowered, and a *narrowed spur* results. There are numerous narrowed spurs near Wellington (fig. 117). When intersection takes place, with the development of a new stream-course across the neck of the spur and the abandonment of that around the end of it a *cut-off spur* is formed (fig. 118).

Exceptionally, in tough, unjointed rocks, vigorous lateral corrasion may undercut cliffs so that they become vertical or even overhang (fig. 119), and so the neck of a narrowed spur may be cut through below but yet remain intact above, forming a *natural bridge*, as in fig. 120. Natural bridges of this kind are less common than those developed by solution in limestone (p. 105).

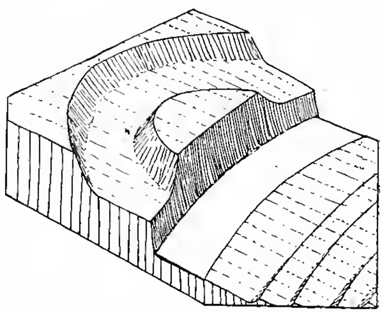


FIG. 118.—Diagrammatic sketch of the remnant of a cut-off spur in the Awatere Valley. The river, now at a level lower than that at which it flowed around the spur, is again cutting outward and destroying the cut-off spur.

Subsequent Lowlands.—The opening-out of valleys both by widening of the floor and grading of the sides naturally goes on much more quickly in weak than in resistant rocks (fig. 121). In a district of alternately weak and resistant rocks, therefore, the subsequent valleys along zones of weak rock and those portions of transverse valleys that cross weak zones are not only mature but broadly opened and reduced to lowlands, while the transverse streams are still cutting through the resistant rock strata in young steep-sided, rock-walled gorges. Gorges of this kind, cutting through strike ridges, are termed *water-gaps* (fig. 122). Sometimes a river that has been cutting a water-gap is diverted by capture while the general lowering of the land-surface is in progress. The abandoned gorge remains as a notch in the crest of a ridge, and is termed an *air-gap*, or *wind-gap* (*a*, *a′*, fig. 122). The air-gap is deep (*a*) or shallow (*a′*), according to the amount of general

lowering of the surface that has taken place since the gorge, or wind-gap, was abandoned.

Wide Valley-plains.—After the limit of size has been reached for curves, these being now fully developed meanders, the width of the valley-floor is greater than that of the belt (*meander-belt*) between lines tangent to the outer curves of the meanders (fig. 115). Every meander is not now cutting against the valley-side. The meander-belt is not constant in position, however—it swings from side to side; and occasionally the stream impinges against and undercuts a portion of the valley-side (4, p. 537). Thus widening still goes on, though less systematically than formerly, the steep bluffs produced by lateral corrasion being perhaps graded and reduced to gentle slopes before another slice is removed.

F. G. Radcliffe, photo.

Fig. 119.—An overhanging cliff developed by lateral corrasion of a stream cutting down and enlarging a curve, the "Dress Circle," Pipiriki–Ohakune Road, N.Z.

Interfluves may be cut through by planation, and capture (*abstraction*) of smaller streams by their larger neighbours may take place as a result. Eventually adjustment to structure may be in part destroyed by this process.

Underfit Rivers.—By the time a valley-bottom has been opened out to a valley-plain the banks of the river flowing in it are formed almost everywhere of alluvium. This lies on a rock floor, which was cut by the river during the process of widening the valley-bottom, and is therefore at least as deep as the bottom of the

H. E. Gregory, photo.

Fig. 120.—The Rainbow Natural Bridge, Utah, U.S.A.

C. A. Cotton, photo.

Fig. 121.—Lowland of small relief (across the middle of the picture) developed by erosion on weak rocks while the outcrop of a more resistant formation still forms a prominent homoclinal ridge (seen in the distance on the right). (The lowland is somewhat dissected owing to recent renewal of the down-cutting activity of the streams crossing it.) Coverham, Clarence Valley, N.Z.

river. From the time when deposition of alluvium in the valley begins, a certain amount of water of the river seeps through it; and by the time that the flood-plain is continuous the underflow is considerable. This is really a movement of the ground-water, but, as the alluvium generally contains more open spaces, is more permeable, and thus offers less resistance to the down-valley flow of the upper layers of the ground-water than does the bed-rock underneath, the presence of the layer of alluvium results in a reduction of the amount of water flowing above ground in the open channel of the river.

The volume of the river being thus reduced, it loses energy and is unable to carry the whole of its load. It aggrades, and, as the thickness of the layer of alluvium increases, the amount of under-

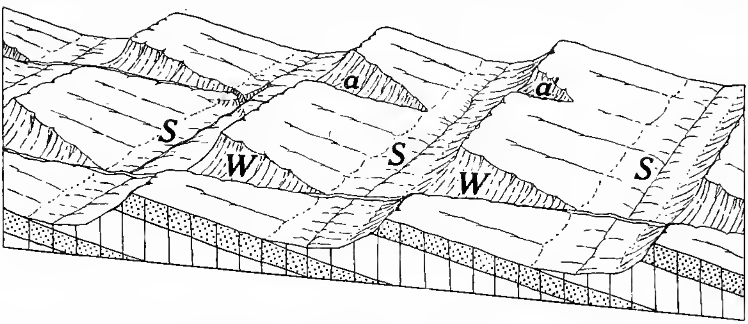


Fig. 122.—Diagram of subsequent lowlands, water-gaps, and air-gaps. *S*, subsequent lowlands; *W*, water-gaps traversed by transverse river; *a*, *a′*, air-gaps.

flow increases also, causing further diminution in the volume of the stream and further aggradation. Owing to this cause alone the thickness of the deposit of alluvium in the valley may become considerable; and also the volume of the river may be so reduced that it is obviously a *misfit—i.e.*, it appears too small to have eroded the valley in which it flows. A misfit of this kind is termed an *underfit* river (Davis, 37). It develops small meanders, proportionate in size to its diminished volume, and these are superposed on the larger curves developed before the shrinkage took place. Similar features are developed in the valleys of streams that have become underfit as a result of the shrinkage in volume due to beheading by capture or by the gradual reduction of their drainage areas by the slow shifting of divides (fig. 72).

CHAPTER X.

THE NORMAL CYCLE: OLD AGE.

General lowering of the surface and destruction of relief. Peneplains. Dissected peneplains. Accordance of summit-levels. Dissected plateaux of different origin. Examples of dissected peneplains.

General Lowering of the Surface and Destruction of Relief.—The inevitable result of the uninterrupted action of the agencies which are at work widening the flat floors of river-valleys and lowering the interfluves is the reduction of the whole, or almost the whole, surface of a region to very faint relief. Plains built up of alluvium deposited by streams that have lost volume as a result of underflow or other cause will eventually be gradually cut down again, and in late maturity graded streams in general are cut down to lower levels than in early maturity owing to the reduction in the supply of waste to the rivers when the relief of the interfluves is reduced. Such lowering takes place so slowly, however, that widening-out of the valley lowland goes on continuously with it. The general result is a gradual flattening-out of the whole surface. The *old-age*, or *senile*, stage of the cycle of erosion has now been reached, and the senile surface, approximating to a plain, is termed a *peneplain*.*

Peneplains.—Unlike a valley-plain, which is a true plain produced by the lateral planation of a river, a peneplain is not a flat surface throughout. It consists in part of the broad valley-plains of the rivers that cross it, developed by long-continued river-planation, and in part of intervening areas of low undulating topography with very gentle graded slopes and no rock outcrops (fig. 123).

Above the general level of a peneplain a few isolated groups of hills or even subdued mountains rise, to which the name *monadnocks*†

---

* The term "peneplain" was introduced by W. M. Davis (31; see also various essays in 4).

† Named from a mountain, Mount Monadnock, New Hampshire, U.S.A., which is a typical example.

is given. They are the remnants of dividing ridges or of the mountain-masses where several divides meet, and are composed of the most resistant rocks of the region, for on the outcrops of these the divides have become fixed at an earlier stage of the cycle.

For the development of a peneplain in a region of resistant, or mixed weak and resistant, rocks an enormous period is required—certainly millions of years, and perhaps many millions. The time required for the change from mature relief to senile relief must be many times greater than that taken for the development of mature

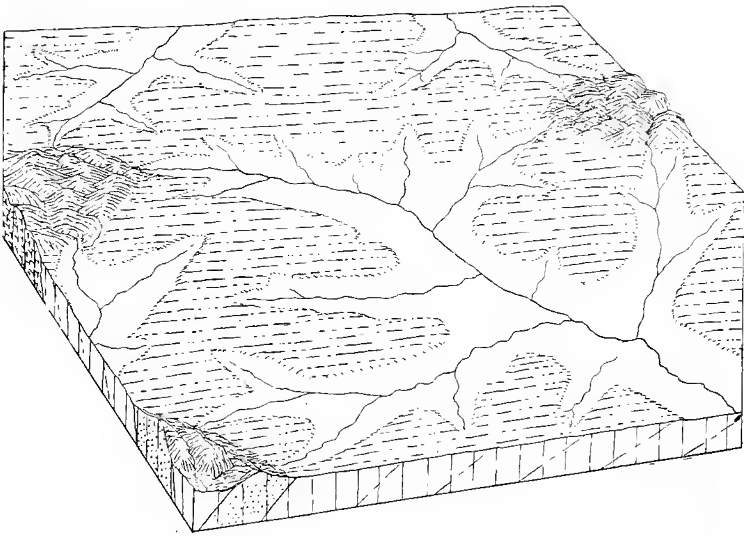


FIG. 123.—Diagram of a peneplain, with monadnocks surviving on the outcrops of the most resistant rocks.

dissection. The amount of material removed from the surface during the latter half of the cycle may be no greater than during the earlier half, but the rate of removal from slopes becomes exceedingly slow as these slopes become gentle. So slow does the mechanical removal of waste from the gentle slopes become that chemical erosion, relatively unimportant in the earlier stages of the cycle, when mechanical erosion was more active, is now responsible for a great part of the lowering of the surface, the material being removed in solution.

As little solid waste is now supplied to streams, the graded slopes in their valleys become very gentle. Under these conditions also the streams develop wide meanders, thus increasing their length and diminishing their slope. The streams become sluggish and have very little energy for corrasion. Still, they have not quite lost the power of cutting laterally, and, as there will now be no rock outcrops, but a continuous mantle of waste over resistant and weak rocks alike, differences in rock-hardness are no longer such effective barriers as formerly, and valley-plains may encroach upon and even cut across the outcrops of resistant rocks formerly marked by subsequent (strike) ridges, to some extent destroying the adjustment to structure developed during maturity. Further adjustment will not take place, as slopes are now too gentle to allow of the formation of new subsequent valleys by headward erosion.

Present-day landscapes belong, as a rule, to one of the earlier stages of the cycle. There have been so many earth-movements in comparatively recent times that the cycle of erosion at present in progress has hardly anywhere advanced beyond the stage of full maturity, except locally on exceptionally weak rocks; but, though young and mature forms are the rule in the current cycle, peneplains developed in earlier cycles have not been entirely obliterated. Some have been uplifted, with the result that they have formed the initial surfaces upon which erosion began to cut the forms of the present cycle. Others have been submerged at various times during the earth's long past history, and preserved beneath masses of sediment.

Dissected Peneplains.—Dissection of a peneplain may generally be ascribed to uplift. Sometimes, however, it may be due to subsidence of the neighbouring land. Where a peneplain is of regional extent some portions of it may be a thousand, perhaps two thousand, miles from the sea, and, since the rivers even on a peneplain must have some declivity in order to flow, it is clear that the central parts may be developed at a height of hundreds of feet above sea-level. Should the central, higher portion of such a peneplain have the sea-margin brought nearer to it by subsidence of a marginal portion, without itself moving either upward or downward, it will be subject to dissection as though it had been uplifted.

Portions of many dissected peneplains still survive as plateaux, more or less dissected (fig. 124), or as occasional flat-topped

C. A. Cotton, photo.

FIG. 124.—Uplifted, but not yet dissected, peneplain, Williams, Arizona, U.S.A. The hills in the background have been built up on the peneplain by volcanic action.

C. A. Cotton, photo.

FIG. 125.—Plateau remnant at a height of 1,350 ft. on the ridge between the Kaiwarra and Makara valleys, Wellington, N.Z. (The floor of the adjacent Makara valley is close to sea-level.)

mountains and ridges in maturely dissected regions (fig. 125). In such cases the peneplain surface may be restored by the imagination by joining up the flat remnants. The restoration thus made may show that, instead of remaining horizontal, the peneplain as it was uplifted suffered deformation, being perhaps irregularly warped or else uplifted as a more or less elongated dome.

Peneplain surfaces survive longest on the hardest rocks, and so even-crested, flat-topped ridges of resistant rock are sometimes found separating low-lying areas of small relief on belts of weaker rock, where the reduction to lowlands of a later cycle is far advanced (fig. 126).

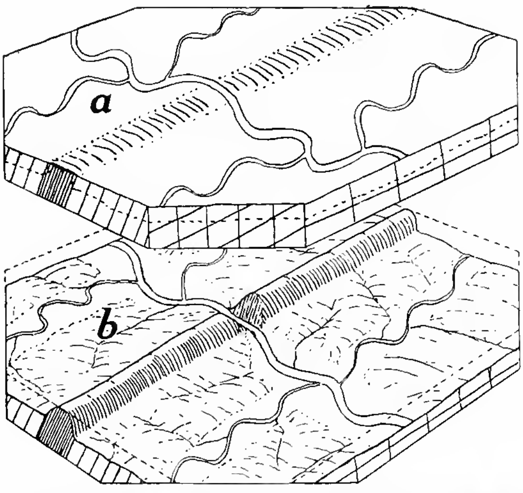


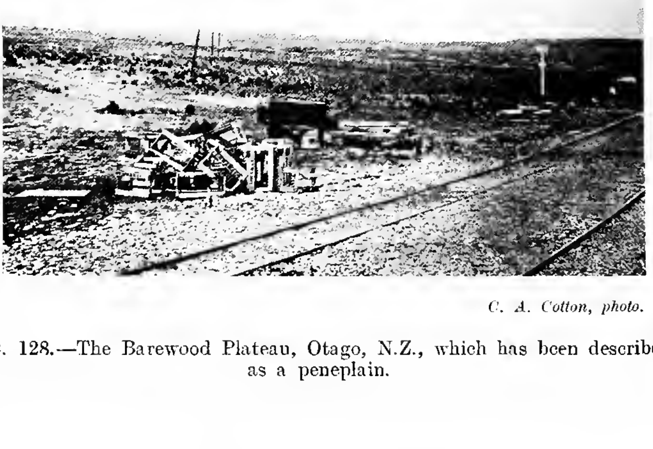
FIG. 126.—Even-crested ridge on the outcrop of a resistant stratum preserving a remnant of the peneplain *a* at a later period, *b*, when weaker formations have been worn down to lowlands.

Accordance of Summit-levels. — Where no flat remnants of a peneplain actually survive, *accordance of summit-levels* (fig. 127) may indicate that a peneplain has been destroyed by erosion, a number of peaks still reaching to about a common level, though the top of each peak must be some little distance below the position of the former surface.

Accordance of summit-levels, unless very well marked, in which case search ought to reveal at least a few flat-topped peaks, does

C. A. Cotton, photo.

Fig. 127.—Accordance of summit-levels in the Richmond Hills, Nelson, N.Z.



C. A. Cotton, photo.

Fig. 128.—The Barewood Plateau, Otago, N.Z., which has been described as a peneplain.

not indicate former planation, or peneplanation, with certainty, for a rough accordance may be expected in the heights of peaks carved by erosion in a district of folded rocks in its first cycle (Daly, 30). Rock-masses which are lifted far above their neighbours tend to sink again owing to their great weight, for there is

C. A. Cotton, photo.

FIG. 129.—Surface of a bench formed by a remnant of a recently uplifted peneplain cut on soft rocks, near Maheno, Oamaru district, N.Z.

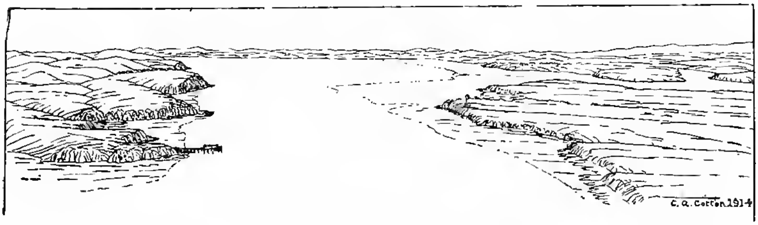


FIG. 130.—Peneplain on soft formations bordering Waitemata Harbour, Auckland, N.Z. On the left and in the distance on the right the relief is stronger owing to the presence of more resistant formations. View looking south towards Auckland.

a limit to the rigidity of the rocks forming the foundations on which mountains stand, and when the limit is passed the deep-lying rocks yield and flow. Some phases of erosion (the rock-breaking processes) are most active also on the highest peaks, and, provided

that the loosened material can slip away down steep slopes as fast as it is broken, to be then removed by streams, differences in height must in this way be reduced; while from Gilbert's law of equal declivities (p. 72)—the tendency to develop slopes of uniform steepness throughout a district of similar rocks—it follows that, if streams are evenly spaced and have cut downward to the same depth, the ridges between them must be reduced to the same height. So it appears that a mountain-range made up initially of a concourse of blocks or arches differentially uplifted, the whole forming—as it probably would—an elongated dome with a very

C. A. Cotton. photo.

FIG. 131.—Slightly dissected peneplain on the soft covering strata of the Maniototo depression, Central Otago, N.Z.

irregular surface, would tend to develop such a measure of accordance of its summit-levels that it would resemble the mountains carved by erosion from the smooth dome formed by a warped, uplifted peneplain.

Dissected Plateaux of Different Origin.—Not even all dissected plateaux have originated as peneplains. Some plateaux in areas of horizontal stratification belong to a rather early stage of the cycle when weak strata have been removed so as to expose the flat surface of a resistant rock high above base-level. So great are the differences in the rate of erosion of different rocks that practically complete removal of the overlying material may take

place, exposing a flat surface over a large area, before appreciable dissection of the underlying rock takes place. If the resistant rock is a stratum underlain by other weak strata it will form a mesa (p. 95).

There are also eroded plains of marine instead of subaerial origin (Chapter XXVII). Some dissected plateaux formerly thought to be of this kind are now regarded as peneplains, and perhaps some that have been thought to be of subaerial origin are really the result of marine planation.

Examples of Dissected Peneplains. — A partly dissected peneplain of wide extent forms part of England, France, and Germany; remnants of a plateau generally regarded as a peneplain form extremely even-crested mountains in the eastern United States; and there is a peneplain of very wide extent throughout eastern Australia, with a few monadnocks rising above it which are remnants of a still more ancient surface of the same kind.

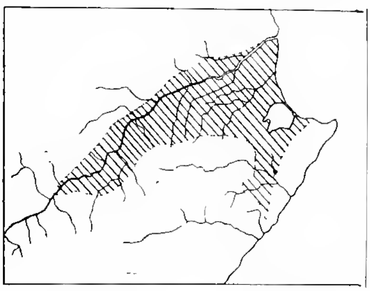


Fig. 132.—The area of weak rocks in the Awatere district, Marlborough, N.Z.

In New Zealand, plateau areas at various levels in Otago (fig. 128), including the flat tops of some mountain-ranges, have been described as parts of a peneplain, either warped or dislocated by faults. The physiographic history of most of these forms, however, and of others like them in various parts of New Zealand (*e.g.*, fig. 149), has been complicated by their having deposits spread upon them prior to their uplift and partial dissection. Further reference will be made to them under the heading "Fossil erosion surfaces" in Chapter XI.

On some areas of very weak rocks at relatively low levels there are, however, remnants of local peneplains which have suffered only from erosion following simple uplift of late date. Perhaps the most conspicuous of these local peneplains is that of the Oamaru district, which is about 400 ft. above sea-level near the coast and is higher inland. It is developed on the softer members of a gently folded series of sedimentary and volcanic rocks the more resistant members of which rise to a greater height in monad-

nocks, a limestone stratum in particular forming prominent ridges. A number of residual areas of this erosion surface exist between the Waitaki and Waianakarua Rivers (fig. 129), though it has been much dissected by the Kakanui River and smaller streams. The part next the Waitaki River bears a deposit of gravel evidently laid down on a wide valley-plain by that river. It is clear from the stage of the cycle of erosion attained in it that the period of still-stand during which this erosion surface was developed was considerably longer than the interval since it was uplifted.

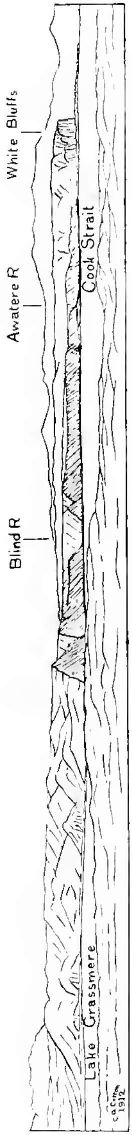


Fig. 133.—Flat-topped ridges and accordance of summit-levels in the Awatere district, Marlborough, N.Z.

There is evidence of similar peneplanation of soft rocks also in Auckland (fig. 130), in Central Otago (fig. 131), and in Nelson (the level of the flat summits of the Moutere Hills) in (geologically) very recent periods of still-stand, which were not necessarily contemporaneous and were probably not terminated simultaneously in all the areas.

On the soft rocks bordering the lower course of the Awatere River, in Marlborough (fig. 132), there is evidence in the form of flat summits, some of them gravel-covered, and in a very complete accordance of numerous summit-levels (fig. 133), that a nearly plane surface had been cut by erosion prior to the succession of movements of even or nearly even uplift which led to further erosion and the development of the present relief. Swinging of the Awatere River undoubtedly planed down much of the surface, forming a wide valley-plain, just as the Waitaki River did in the case of the Oamaru example cited above; but these valley-plains must be regarded as parts of peneplains of wider extent.

These late periods of still-stand, occurring since the latest mountain-building movements in New Zealand (Chapter XIV), were not long euough anywhere to permit of an approach to planation on the resistant rocks of which New Zealand is largely built.

CHAPTER XI.

FOSSIL PLAINS AND SUPERPOSED STREAMS.

Fossil erosion surfaces. Superposed drainage. Conditions of survival of stripped fossil plains. New Zealand fossil plains. Fossil plain or peneplain? Salients on exposed fossil plains. Dissection of the undermass.

Fossil Erosion Surfaces.—A fossil is a thing "dug up," and for the palaeontologist the term "fossil" signifies some part or some trace of an animal or plant buried a very long time ago and either dug up or exposed by erosion very recently. By the term *fossil erosion surface*, therefore, may be understood an erosion surface, whether young, mature, or old, and whether produced by normal subaerial erosion or other agency, which, after coming into existence as such, has been buried by a *cover* of sediment (*covering strata*) and long afterwards exposed by renewed erosion.

Some fossil erosion surfaces can be seen only in profile in quarries, in road-cuttings, or on coastal cliffs or steep valley-sides, where the covering strata still lie on them. Others have been exposed owing to the stripping-away of a cover that is weak compared with the underlying rock (or *undermass*), and so an ancient topography sometimes again forms the surface after having been buried and preserved for untold ages. One such surface of extreme antiquity in the north-west Highlands of Scotland has been in places re-exposed by erosion after remaining buried for perhaps hundreds of millions of years. It is in parts a surface of rather strong relief developed on a hard gneissic rock and covered by weaker sandstone.

Mature or young surfaces, however, are rarely found buried. Fossil surfaces are commonly plains of erosion, and sometimes clearly peneplains, on which the ancient soil may still be recognized, with fragmentary remains of vegetation, covered by terrestrial deposits, which are succeeded generally by marine sediments. In

other cases marine sediments rest directly on the surface of the undermass, which consists of fresh rock evidently planed by wave-action. Even in such cases, however, the surface prior to submergence was quite probably a peneplain, for if submergence took place slowly the waves of the advancing sea would stir up and remove the soil and waste-mantle from the surface, exposing and planing the bare rock.

The junction of a cover of sediments with an eroded *floor* of older rocks is called an *unconformity*. This term indicates that there is a break in the succession of the strata, the cover not lying *conformably* on the strata of the undermass, as is the case with beds deposited one upon another without break. In other words, an interval of time between the period at which the strata of the undermass were deposited and that at which the beds of the cover were spread above it is not represented by sedimentary strata in the district where the unconformity occurs. During this time-interval, or at least the latter part of it, erosion was at work preparing the planed floor on which the cover lies.

In many natural sections in New Zealand strata may be seen lying unconformably on a flat floor—*i.e.*, a fossil plain—which was horizontal at the time the strata were deposited, as is shown by the fact that it is parallel to their bedding. The limestone beds seen in fig. 87, for example, rest on a planed surface of ancient greywacke rocks (exposed on the side of the ravine below the limestone). Many sections in the district show the same relationship of the rocks, and so it is known that this fossil plain below the limestone is of considerable extent. It was planed finally by wave-action, as is shown by its smoothness and by its fresh, unweathered nature. The lowest bed, moreover, of the covering strata, a pebbly layer, is a marine deposit.

Fossil peneplains, and fossil erosion surfaces generally, are not necessarily in their original attitude: some have been tilted and warped or folded, along with the strata that lie on them. Where, as is usually the case, the cover was laid down as horizontal beds on a horizontal floor, the parallelism of at least the lowest beds of the cover with the floor has been preserved, however, though both are warped or tilted.

In New Zealand large areas of the surface are parts of a fossil erosion plain stripped of its weak cover and thus re-exposed. As

a rule, these are no longer horizontal, but are tilted or arched, gently tilted portions being only slightly dissected, while more steeply inclined areas are deeply and maturely sculptured, especially in districts of large rainfall. The best-preserved fossil plains are in Otago, South Canterbury, and northern Nelson. These will be discussed at some length after superposed drainage has been explained in the next section.

Superposed Drainage.—Where a cover lies unconformably on an undermass with different structure, neither the form of the buried surface nor the structures underlying it can in any way influence the direction of the streams on the cover. Streams consequent on the slopes of the surface and beds of the cover or subsequents adjusted to its structure will, as a general rule, have courses that are entirely out of adjustment with the rocks, and perhaps also with the form of the surface, of the undermass. So long as the undermass remains entirely buried there is no apparent anomaly, its surface form and its structures being either unknown or having been revealed only by boring or by mining. With deeper erosion, while considerable areas of the cover still survive, even though the deeper valleys have been cut down through it into the undermass, the relation of stream-courses to the cover is still obvious.

Stream-courses that have been cut down through the rocks on which they were developed into rocks of different structure, to the stratification and other structures of which they can have neither a consequent not a subsequent relation, are termed *superposed.* In general they are superposed from an unconformable cover on to the rocks and rock structures across which they now flow. Those that were consequents before they became superposed are now *superposed consequents*, and those that were subsequents adjusted to the structures of the cover are now *superposed subsequents.*

Streams superposed on an undermass and incised in it by farther valley-deepening are thereby fixed in position, just as are consequents incised beneath an initial surface. As local base-levels sink beneath the surface of the undermass, complete removal of the cover from the adjacent area will follow in the course of the erosion cycle, and, as this proceeds, all the streams, small as well as large, will become superposed. Thus the entire drainage pattern from the cover is stencilled on the undermass, while the cover itself disappears.

Systems of valleys with definite patterns resulting from superposition are known in various parts of the world. Systems of parallel valleys cutting transversely or diagonally across the strike of the rocks may be superposed subsequents, while a not uncommon grouping of superposed consequents is a radial arrangement indicating the presence of a dome-shaped uplift of a former cover* (see fig. 134, *A*).

In New Zealand superposed consequent streams are very common, especially in the South Island, draining uplifted areas from which a cover has been lately stripped, leaving exposed parts of a fossil erosion plain, which will be referred to again below.

Streams may also be superposed from courses, in a general way consequent on the form of the uplift, which they take down the apron of waste (Chapter XV) accumulating along the base

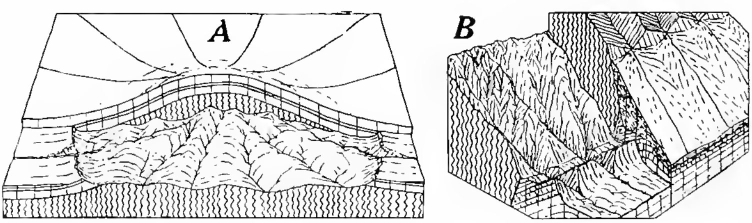


Fig. 134.—Diagrams of superposed drainage. *A*, radially arranged superposed consequents; *B*, transverse streams superposed from courses guided by the slope of a temporary accumulation of waste. In both diagrams the early drainage pattern, before the removal of the cover, is also shown.

of a newly formed mountain-range, the front of which forms an unusually steep declivity of the initial surface (see fig. 134, *B*). When, later, general reduction of the uplifted surface by erosion is accompanied by removal of the apron of waste, and the stream pattern from it is stencilled on the underlying rocks, the streams are generally quite out of adjustment with the rock structures across which they flow.

Superposition of this kind may perhaps correctly be invoked to account for the numerous transverse streams across a homoclinal ridge which lies close along the base of the Kaikoura Mountains

* *E.g.*, in the English Lake District, described by Marr, 15, pp. 145–46.

on their south-eastern side (figs. 85, 135). The peculiar branching of some of these streams, which takes place upon the outcrop of the thick limestone of the ridge, isolating island-like masses of it between the branches (fig. 136), is a phenomenon resulting appa-

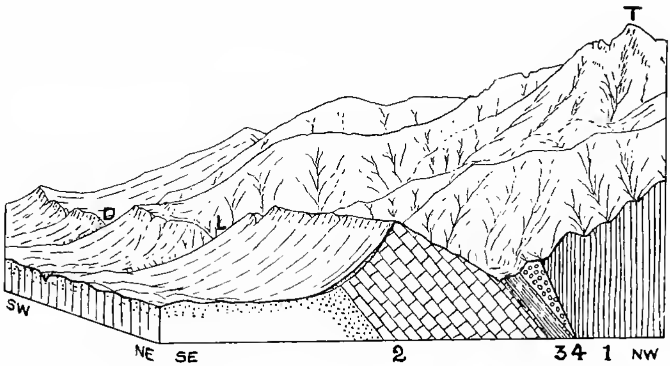


FIG. 135.—The south-eastern slope of the Kaikoura Range, N.Z., including Mount Tapuaenuku (T), showing the gorges (D and L) of two transverse streams (probably superposed) through the homoclinal ridge along the base of the range. The front profile shows the structure. The formations 2–3, in a homoclinal attitude, are separated from those forming the higher part of the range (1) by a great fault (4).

rently from some cause other than headward erosion, and points to superposition of some kind.

Though the foregoing explanation is probably correct in the case cited, it is possible, however, that some such transverse courses across strike ridges in the foothills of mountain-ranges were developed originally as ordinary consequents on the simple slopes of a surface high above the present one and separated from the rocks at present exposed by a great thickness of beds since removed by erosion, all of which may be conformable to one another, though the upper members may have been much less closely folded than the deeper beds. The transverse streams might still be described as superposed, but in this case from a conformable instead of from an unconformable cover.

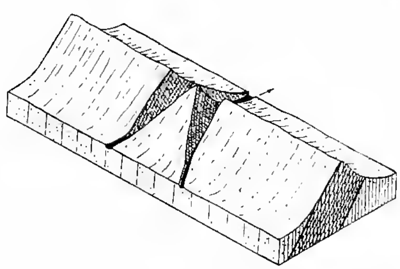


FIG. 136.—Diagram of the fork of a stream superposed on a homoclinal ridge.

Several south-westward-flowing streams which join to form the Spey, a tributary of the Conway River, in southern Marlborough, N.Z., seem to be of superposed subsequent origin. They cross close-set, prominent strike ridges, or hogbacks, (shown in fig. 89) nearly at right angles, and are thus obviously not in adjustment with the structure of the rocks across which they flow; nor do they descend the average slope (towards the north-west) of the block of country in which they occur in a way that would suggest a consequent or superposed consequent origin. They are, however, parallel in a general way to the strike of somewhat folded covering beds which are preserved in a depression a short distance away to the north-west (see fig. 137), and which certainly covered formerly a much larger area of the higher country. The streams were apparently developed as subsequents adjusted to the structure of these beds. If superposed on the undermass from such courses on an unconformable cover they should, therefore, be described as superposed subsequents.

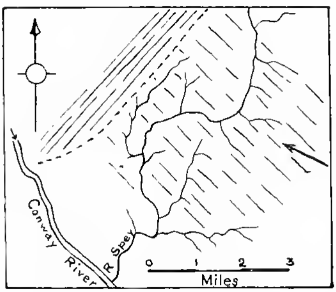


FIG. 137.—The streams of the Spey system, which are probably superposed subsequents. \\\, undermass; ///, cover. The large arrow indicates the average slope of the surface.

Since superposed stream-courses result from the removal of beds differing in structure from those below and generally unconformable to them, it follows that they are often associated with fossil plains. This association is not, however, a necessary one, for superposition of streams does not require that the undermass shall be any more resistant to erosion than the cover. Where they are about equally resistant, or the cover is more resistant than the undermass, the latter will be thoroughly dissected by the time the former is all removed.

When dissection takes place, whether at once or later—*i.e.*, after the destruction of a fossil plain—modification of the superposed drainage pattern will take place, partly by the formation of new insequent streams, but chiefly, where the undermass is not homogeneous, by the development of an entirely new system of subsequent courses adjusted to its structure.

Conditions of Survival of Stripped Fossil Plains.—The stripping of the cover from fossil plains and the survival of the surfaces to form prominent features of a landscape depend, above all, on the relative resistance offered to erosion by the undermass and the cover. Stripping is favoured by the tilting of strips or blocks of country, but survival of the fossil plain may be expected only where the angles at which they are tilted are moderate, the permissible slope being steeper in a dry than in a wet climate.

Fossil plains are known that have been uplifted bodily so that they retain their original horizontal attitude scarcely modified (fig. 138); but it will simplify this discussion to consider the case in which tilting has taken place to a moderate extent (fig. 139).

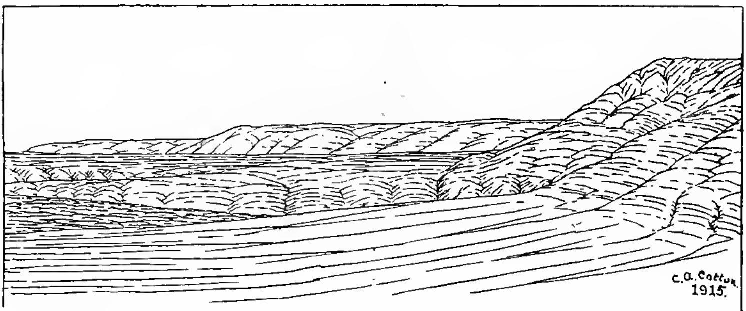


FIG. 138.—Stripped fossil plain of Central Otago, dislocated by faults so that portions stand at various levels but are still nearly horizontal. Low level, Barewood Plateau; high level, right, Rock and Pillar Range; distance, Lammermoor and Lammerlaw Ranges.

On such a surface, when first uplifted, numerous consequent streams will come into existence, and these will be approximately parallel if the tilting is uniform. They will soon be actively engaged in grading their courses. In streams such as these, with initially steep declivities, this process involves simultaneous corrasion throughout their length, but the lower courses will, on account of the greater volume of the streams, be deepened first, and when the graded condition is approached the maximum valley-depth will be found in the middle courses.

From the rapidly deepened consequent valleys insequent tributaries will be developed, and perhaps also subsequents. Thus, since the spacing of the consequents alone may be close and the texture of dissection becomes finer when insequents and subsequents

have also been developed, deep entrenchment of the whole system beneath the sloping surface of the weak covering strata must rapidly take place. Maturity of dissection will be rapidly attained, first in the middle part of the slope, and later over the whole area of the surface.

The consequent and other streams of the sloping upland, when they cut through the cover and become superposed on the resistant undermass, will receive a check, and the rate of farther downward cutting will become comparatively slow. Before this stage is reached the measure of the relief has been increasing progressively with downward cutting, and even after this stage it may still increase,

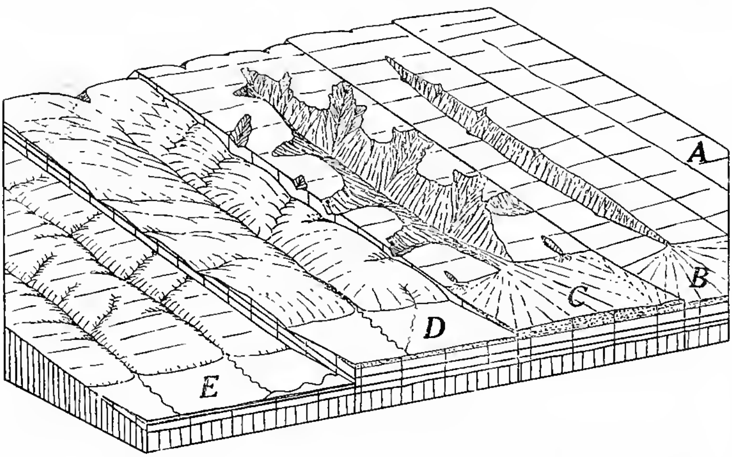


Fig. 139.—Diagram of the development of the surface of a gently tilted area with a relatively weak cover and resistant undermass. *A*, initial form; *B*, *C*, and *D*, early sequential forms; *E*, stage at which the fossil plain is exposed.

though very slightly, if maturity of dissection of the surface is still to be attained. After the attainment of maturity reduction in height of the interfluvial areas of weak covering strata may go on more rapidly than vertical stream corrasion on the resistant underlying rocks, and the measure of the relief may be thus reduced. Even if the streams had attained grade without cutting through the cover in the early stages of dissection, after the cover has been largely removed from the higher part of the block they will be forced to cut deeper and will eventually become superposed. Later, when the

covering strata have been largely or wholly removed from the whole sloping surface, all the streams will be incised to some extent in the undermass. Owing to the resistant nature of the rocks of the undermass, however, the ravines in it will for long remain narrow, *simulating* youth, while on the interfluves inclined flat areas will survive where the ancient eroded floor has been stripped of its cover (fig. 139, *E*; also fig. 140). This stage will be attained earliest at the middle parts of evenly sloping surfaces, for half-way down the slopes stream corrasion has resulted in the greatest valley-deepening and the greatest development of tributaries. Farther down the slopes, owing to smaller depth of corrasion, undissected interfluval areas are likely to be larger; and farther up, as the general inclination is not steep, there will be little

C. A. Cotton, photo.

FIG. 140.—Partly dissected stripped fossil plain, near St. Bathans, Central Otago, N.Z.

concentrated wash. So in both these positions remnants of the cover may be expected to survive longer than in the middle of the slopes.

New Zealand Fossil Plains.—This is the stage of erosion that has been reached on large areas of upland surfaces in various parts of New Zealand. They are now sloping fossil plains almost entirely stripped of their cover, and crossed by many steep-sided, generally superposed consequent ravines, which increase rapidly in depth as followed up-stream from their debouchures, with occasional salients formed by remnants of the covering strata relieving the otherwise flat interfluvial surfaces.

The most perfect examples are those forming the back slopes of some of the "block mountains" of Central Otago—*e.g.*, the western slope of Rough Ridge (figs, 141, 142); a long north-easterly slope

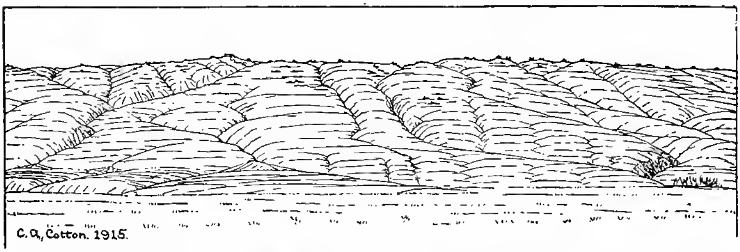
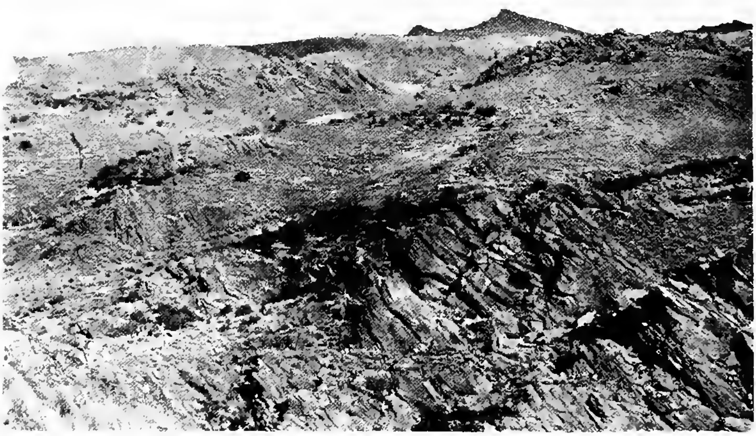


FIG. 141.—A north-westward-sloping fossil plain forming part of Rough Ridge, Central Otago, N.Z., which descends in the foreground beneath covering strata.



C. A. Cotton, photo.

FIG. 142.—Detail view of part of the back slope of Rough Ridge, shown in fig. 141

from the broken plateaux of Central Otago to the depression followed by the Shag River (fig. 143); a similar slope, though rather more maturely dissected, descending south-eastward to the Taieri Plain (fig. 144); a similar slope descending north-eastward from the Kakanui Mountains towards the Oamaru district (fig. 145); the

westward slope of the Hunter's Hills (fig. 146), with which are associated other similar slopes surrounding the depression that forms the Waihao basin, descending westward to the Hakataramea Valley, and extending as far as the Waitaki River; and a gently

C. A. Cotton, photo.

Fig. 143.—Fossil plain descending to the Shag Valley, N.Z., from the south-west. A residual hill of the cover, capped by lava, is on the distant sky-line. The foreground consists of subdued hills of the covering strata not far above local base-level. The Shag River is in the centre.

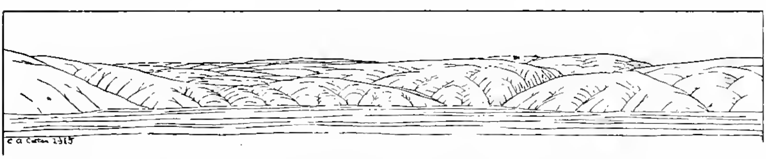


Fig. 144.—Undulating fossil plain descending to the Taieri Plain, Otago, N.Z., from Central Otago. Debouchure of the Taieri River to right of centre.

sloping plateau which descends north-westward from the base of the Haupiri Mountains towards the Aorere River, northern Nelson (fig. 147).

The more nearly level parts of the Otago fossil plain, forming the Barewood Plateau, have been called the "Central Otago

peneplain" (figs. 128, 148); and another area of similar surface, which remains approximately level and is but little dissected, though between two and three thousand feet above sea-level, forms the Gouland Downs, in northern Nelson (figs. 60, 149, 190–192).

C. A. Cotton, photo.

FIG. 145.—A portion of the fossil plain which slopes from the Kakanui Range towards Oamaru and underlies the extensive covering beds of that district. This view shows the surface trenched by the Waianakarua River, a superposed consequent stream.

A somewhat similar surface, but dissected, has been recognized forming the summits of the Kaimanawa Mountains, in the North Island (Speight).

Fossil Plain or Peneplain?—In the case of some of the examples cited the cover has consisted of marine formations, while

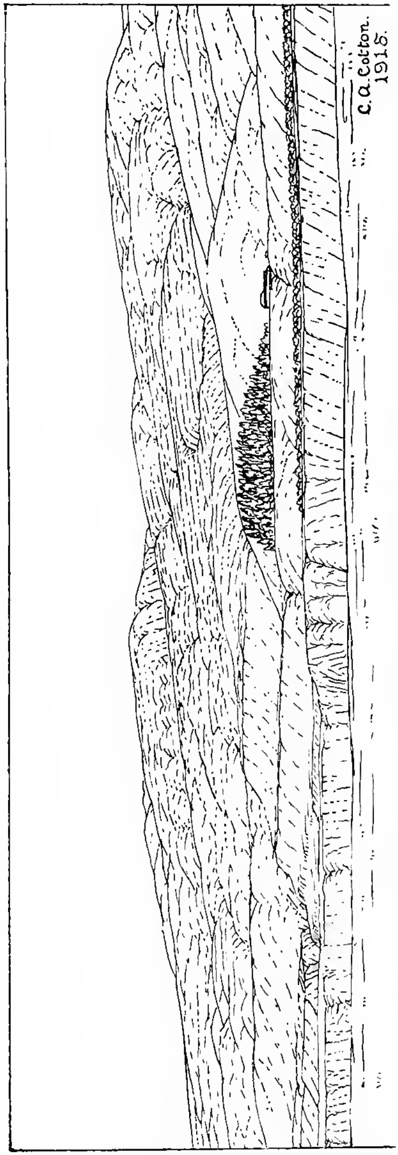


FIG. 146.—Tilted fossil plain forming the western slope of the southern end of the Hunter's Hills, South Canterbury, N.Z. In the middle distance the slope descends beneath the covering beds in the Waihao basin.

other parts of the great fossil plain were buried beneath terrestrial deposits. Presumably still other parts of the same great plain of

erosion remained emergent as a peneplain, but they are not distinguishable on the evidence at present available. In most places the evidence as to the "fossil" nature of the surface is clear. Either the surface slopes down and disappears below thick beds of the cover still resting on it in a neighbouring depression (fig. 150), or outliers of the cover still survive here and there on the upland surface, or *sarsen stones* lie about. These are remnants of some unusually resistant bed in the cover which broke up owing to the removal of the softer material on which it rested. The fragments, though much reduced in size by weathering, still litter the surface of the undermass. Small examples of sarsen stones of a hard cemented quartz grit or conglomerate are common in many parts

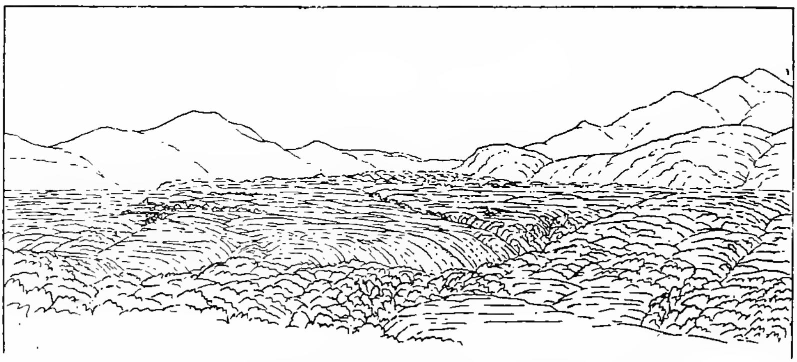
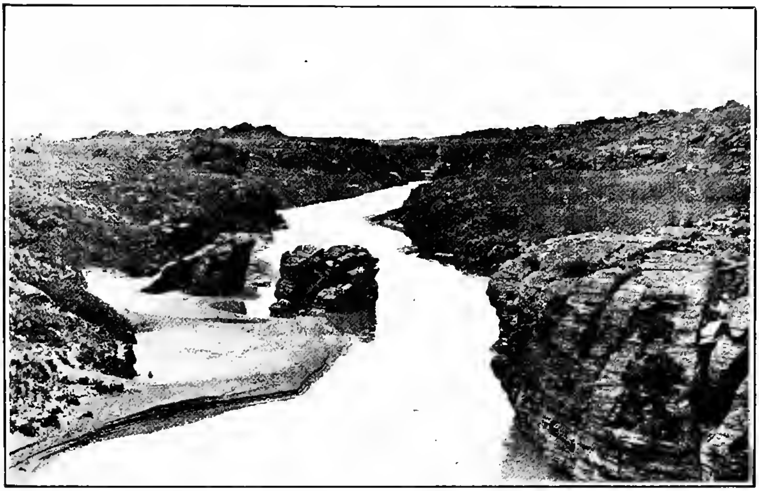


Fig. 147.—The sloping plateau, a fossil plain, forming the south-eastern side of the Aorere Valley depression, northern Nelson, N.Z. (After a photograph by the N.Z. Geological Survey.)

of Otago, testifying to the former presence of a widespread cover, and in places they are so numerous and large as to be very conspicuous (fig. 151).

Salients on Exposed Fossil Plains.—Salient features may be present, breaking the even surface of the undissected parts of a stripped fossil plain. Some such salients may be re-exposed monadnocks, but on the New Zealand plateaux the commonest salients are remnants of the covering strata, which often assume subdued forms that resemble monadnocks (fig. 143), though some are clearly recognizable from their form as mesas and buttes (fig. 152). They may owe their preservation to local induration, to



C. A. Cotton, photo.

FIG. 148.—Horizontal fossil plain near Barewood, Otago, N.Z., crossed by the superposed consequent course of the Taieri River, which farther down-stream occupies a cañon nearly 1,000 ft. deep.

C. A. Cotton, photo.

FIG. 149.—The Gouland Downs, northern Nelson, N.Z., a fossil plain. A few residual mesas of the limestone cover, which are forested, show up in contrast with the treeless plateau.

local thickening of a resistant stratum, or to the presence of lava-flows of small extent. Such salients occur sporadically; but others may be definitely related to small inequalities of uplift which have caused unusually wide spaces between the consequent streams.

Dissection of the Undermass.—Where there is such an adjustment of the slope of the surface to the volume of the streams

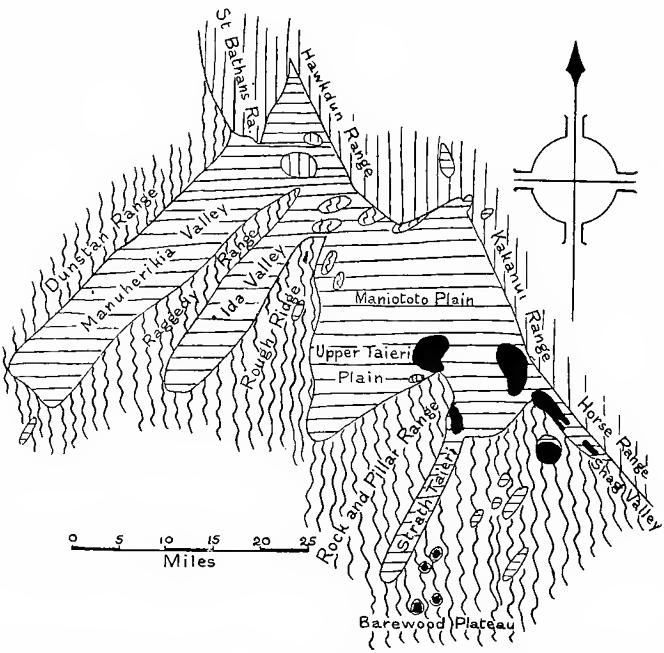


Fig. 150.—Geological sketch-map of part of Central Otago, N.Z., showing the distribution of the undermass, which is exposed as stripped fossil plains on the upland surfaces, and the covering strata, which still overlie the undermass in the depressions. The areas in which schist undermass rocks reach the surface are marked by waved north–south lines, the areas of greywacke undermass by straight north–south lines, and those in which the covering beds form the surface (or underlie only a thin layer of alluvium) by straight east–west lines. Volcanic rocks in the cover are shown in black.

that the latter are graded while not deeply incised, stripped fossil plains traversed by ravines of moderate depth will escape dissection and will survive for a long time. In a region of small rainfall an initial slope as high as 10° may have resulted in the development

of small consequent streams none of which has become a master, and thus a large number of subequal, graded, but still shallow ravines occupied by intermittent streams will traverse the surface. These will destroy the continuity of the surface to some extent, but,

J. Park, photo.

FIG. 151.—Sarsen stones on the partly dissected fossil plain of Rough Ridge, German Hills, Otago, N.Z.

unless the stream spacing is very close indeed, the plateau remnants on the interfluvial areas will then be relatively stable.

As the ravine-sides become graded by soil-creep the sharp shoulders which will at first bound the plateau remnants will early

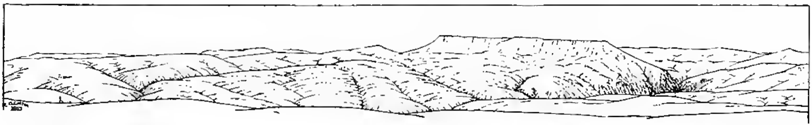


FIG. 152.—Part of the fossil plain which descends from the Kakanui Mountains towards Oamaru, N.Z., showing a large residual mesa of the cover.

disappear. The interfluvial areas will thus be reduced to broadly convex, subdued forms; but still their summits will be accordant with one another, allowing the eye to reconstruct the destroyed tangent surface of the undermass.

These are the conditions obtaining over considerable areas of the fossil plain of South Canterbury and Otago. Such a surface will waste away very slowly as a whole, suffering little change of form, as long as it is subject only to the action of the streams already developed on it.

Under other conditions irregularly uplifted plains, whether of fossil-plain, peneplain, or other origin, are relatively short-lived. If, owing to abundant rainfall, to steepness of initial slope (fig. 153), or to initial irregularities of surface which have resulted in concentration of consequent drainage into a few streams, the graded profile for the dissecting streams lies far below the uplifted surface (see, *e.g.*, the deep gorge of the Waianakarua River in fig. 145), the remnants of it will be attacked on all sides owing to the deepening and widening of consequent, nsequent, and perhaps subsequent ravines, and to their headward erosion. A fossil plain thus attacked may be destroyed progressively as it is exposed by the removal of the cover, and, where these conditions are extreme, a stage will early be reached at which dissection is deep and complete, except in a strip along the top of the slope, where dissection may be expected to lag somewhat. Here remnants of a fossil plain may be found (figs. 153, 154), and even perhaps patches of the cover.

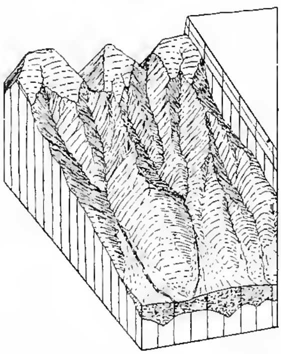


FIG. 153.—Dissection of a somewhat steep slope by vigorous streams. The initial surface (of a weak cover lying on a resistant undermass) is shown on the right. A strip of fossil plain survives at the top of the slope, but this is partly destroyed by streams from the opposite side, where there is a fault-scarp (Chapter XII).

On the lower slopes the number of ravines will be reduced in the struggle for existence among the streams (fig. 153), and between those that survive the ridge-crests will descend with a more or less even slope, so that a general rough accordance of summit-levels with a sloping surface may still be traceable.

Sloping surfaces in this stage of dissection are rather common in New Zealand. As examples may be cited the eastward slope of the Pikikiruna Range, descending towards Tasman Bay (fig. 154), and the more deeply cut north-western slopes of the Kaikoura and Seaward Kaikoura Mountains. The accordantly-sloping spurs of the last-mentioned range, descending to the Clarence Valley, are shown in fig. 184.

C. A. Cotton, photo.

FIG. 154.—Remnant of a rather steeply inclined fossil plain (on the right) at a height of about 3,000 ft. at the crest of the Pikikiruna Range, N.Z. Farther down the slope to the right (to the east, towards Riwaka and Tasman Bay) this surface is completely destroyed by erosion, its form being indicated only by the tapering spurs between the deeply cut valleys. On the left is the crest-line of the fault-scarp shown in fig. 193.

CHAPTER XII.

LAND-FORMS ASSOCIATED WITH FAULTS.

Faults and their effects. Fault-scarps. Fault-blocks and block mountains. Cycle initiated by "blocking" movements. Fault valleys and fault-line valleys. Dissection of fault-blocks. Dissection of fault-scarps. Rejuvenated fault-scarps. The recognition of fault-scarps.

Faults and their Effects.—In order to simplify the presentation of the concept of the cycle of erosion, in the foregoing chapters the assumption was tacitly made that in the production of such irregularities of surface as were formed during the uplift that initiated the cycle faulting (p. 15) had no part, upswelling and arching of the surface and of the underlying beds of rock taking place by bending (*warping*) without breaking. In addition to such deformation by warping, however, some actual breaking (*faulting*) generally occurs when differential movement of adjoining areas takes place. The movement along faults may be quite subordinate to warping and folding; but, on the other hand, it predominates in some cases over all other kinds of deformation, producing very striking results. In the present chapter, therefore, the results of the presence of faults will be discussed—not only faults formed during the earth-movements that initiate the cycle, but also more ancient faults, for these, if present, equally complicate the structure of the rocks.

Fault-scarps.—Where faulting has just taken place, actual breaks of the surface occur—sudden descents from the high-standing to the low-lying sides of the faults. These are *fault-scarps*.* They form striking landscape features in the early stages of the cycle introduced by the movements associated with the faulting. In soft material, such as that immediately underlying a newly uplifted

* See especially Davis, 4, pp. 725–72; 35.

sea-bottom, they are very quickly destroyed by erosion; but they are longer-lived in cycles introduced by uplift and deformation of pre-existing land (generally composed of more resistant rocks), and also where newly uplifted sea-bottom or alluvial accumulations are thin and rest on resistant rocks, which are exposed in the initial fault-scarps. The latter is commonly the case in New Zealand.

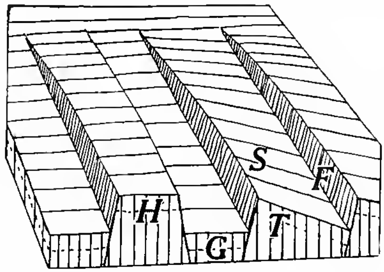


FIG. 155.—Diagram of elongated fault-blocks.

Fault-blocks and Block Mountains.—Faults commonly occur in groups, the members of a group being roughly parallel to one another; or there may be two intersecting systems of fractures. In the latter case the region is cut up by the faults into quadrilateral areas termed *blocks*, which have moved up or down independently of one another. Where there is only one prominent system of faults elongated blocks result, which are terminated by warped surfaces instead of cross-faults (fig. 155).

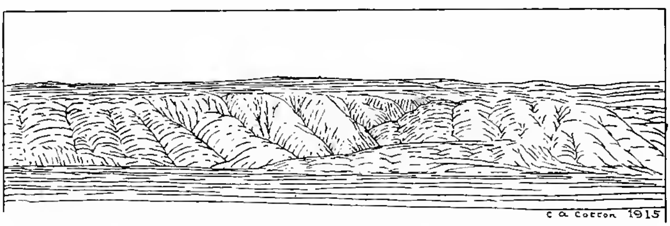


FIG. 156.—A distant view of the Rock and Pillar Range, Central Otago, N.Z., as seen from the north-west, across the Upper Taieri Plain. The slight inclination of the highland plateau towards the north-west shows that the block is not quite evenly uplifted. The present height of the scarp on the low side (shown in the sketch) is, however, about 3,000 ft.

The movement of a block may be uniform throughout a particular cross-section, the block having simply sunk or risen so as to form, in the one case, a trough, or *graben* (*G*, fig. 155), or, in the other, an uplifted block, or *horst* (*H*), bounded on both sides

by fault-scarps. The Upper Taieri Plain (the southern part of the Maniototo Plain) is a graben (fig. 161), while the Rock and Pillar Range, adjacent to it, is a horst, though uplifted not quite evenly (figs. 156, 161). Another very distinct graben forms part of the valley of the Waitaki River (see figs. 157, 175).

Some blocks, on the other hand, may be *tilted*, so that one side is relatively uplifted and the other relatively depressed (fig. 155, *T*; see also figs. 157, 158). A tilted block is bounded by a fault-scarp only on the relatively uplifted side, and from the crest-line at the top of this scarp an inclined *back slope* (fig. 155, *S*) descends, and ends generally in a *fault-angle* at the base of the scarp bounding the next upland block (fig. 155, *F*; also figs. 158, 159). A tilted block thus shows some resemblance to an unsymmetrical

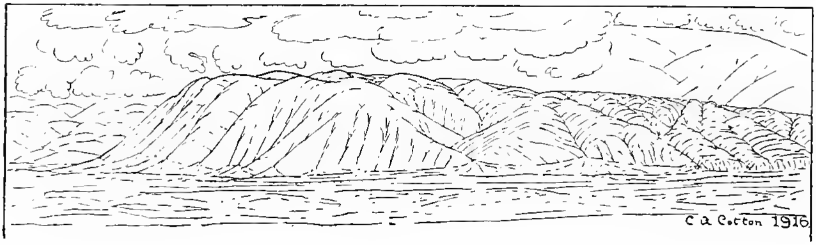


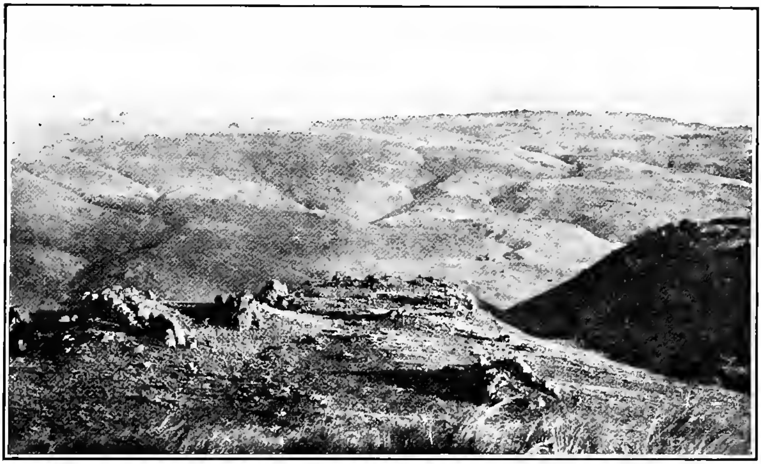
FIG. 157.—Small tilted block (behind Kurow) in the complex graben of the Waitaki Valley, N.Z. The height of the scarp at the eastern (left) end of the block is about 1,000 ft. Part of the main southern wall of the graben is seen in the distance on the right.

fold of the land-surface of which the steeper side is replaced by a fault, and the resemblance becomes very close where the crown of a block is arched, as assumed in fig. 160 for the initial form of the Kaikoura and Seaward Kaikoura Ranges. The resemblance of block structure to anticlinal structure is emphasized also where faults are in part replaced by sharp warps (termed *monoclinal folds* or *flexures*).

Mountains carved by erosion from large uplifted earth-blocks bounded on one side or both by fault-scarps are termed *block mountains*. Broad landscape features, such as block mountains and the depressions between them, which are due to earth-movements are described as *tectonic*, in order to distinguish them from forms developed entirely by erosion.

Cycle initiated by "Blocking" Movements. — In a cycle initiated by rapid movements in which faulting is prominent the inequalities of the initial surface will give rise to the usual features characteristic of youth, such as, for example, consequent lakes (on the low-lying blocks) and consequent falls (where consequent streams descend fault-scarps). Draining of the lakes and grading of the stream-courses and of the general surface proceed on the same lines as in the cases already discussed.

If the deformation takes place more slowly—*i.e.*, not so rapidly that it may be considered instantaneous from a geological point of



C. A. Cotton, photo.

FIG. 158.—View looking across a narrow fault-angle depression at the back slope of a tilted block from the crest-line of another. Low range east of Strath Taieri, Otago, N.Z.

view—there will be a smaller development of initial lakes, for the outlets from enclosed basins will be cut down to some extent by the streams that drain them as the enclosing blocks rise across their paths. Erosion also will be very active on the rising blocks, supplying much waste to be deposited, temporarily at least, in the depressions, so that deposits of alluvium forming *basin-plains* (Chapter XVIII) may entirely or almost entirely take the place of consequent lakes.

Also, where deformation goes on slowly it may be irregular, now one area being uplifted and now another. Thus rivers that are strictly consequent on the earlier movements of a series, and which become fixed in their courses owing to their own activity

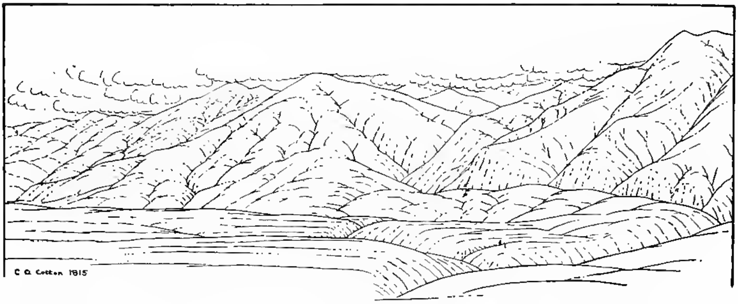


FIG. 159.—Fault-angle depression occupied by the Shag River, Otago, N.Z. The evenly tilted surface in the foreground (a fossil plain stripped of its cover since the fault-angle was formed) descends to the base of the maturely dissected fault-scarp of the Kakanui–Horse Range. View looking north-east.

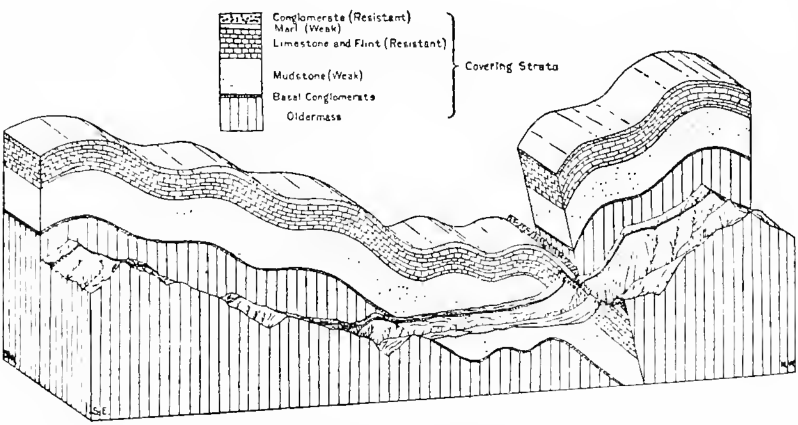


FIG. 160.—Diagram illustrating the type of structure and sculpture in the Kaikoura and Seaward Kaikoura Ranges and the intervening fault-angle depression (the Clarence Valley). The front strip of the diagram illustrates the present stage of dissection.

in down-cutting, may not occupy what are eventually the lowest tectonic gaps. Such courses are termed *anteconsequent* (91). They are further discussed in Chapter XVIII.

The principal consequent, or perhaps in part anteconsequent, river-courses traverse the lower-lying blocks and the fault-angles between tilted blocks—perhaps expanding here and there initially into lakes. They may follow very irregular, zigzag, and roundabout courses, as they must skirt and avoid the higher-standing blocks (fig. 161). The courses of many of the large rivers of New Zealand are clearly seen to be directly consequent on such "blocking"

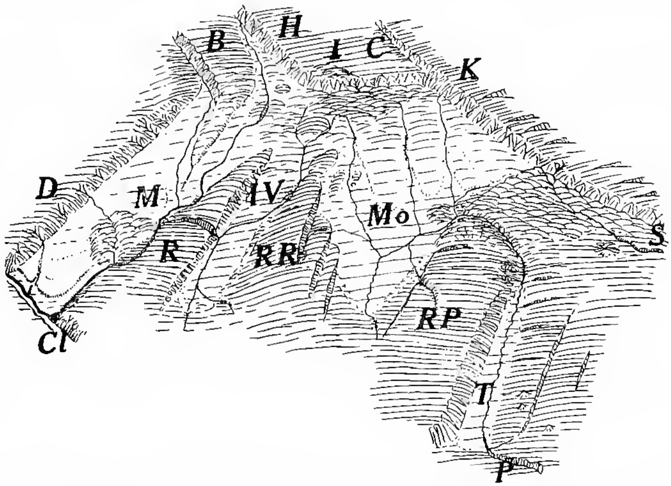


Fig. 161.—Generalized diagram of part of Central Otago, N.Z., showing block mountains and depressed blocks, and displaying the consequent nature of the Shag and Taieri Rivers and of some tributaries of the Clutha. The district is shown as it appears at present, when the fault-scarps have been somewhat dissected and the soft covering strata (still present in the depressions) have been stripped from the upland surfaces, exposing fossil plains (compare fig. 150). *D*, Dunstan Mountains; *M*, Manuherikia Valley; *R*, Raggedy Range; *IV*, Ida Valley; *RR*, Rough Ridge; *Mo*, Maniototo Plain; *RP*, Rock and Pillar Range; *T*, Strath Taieri and Taieri River; *P*, Barewood Plateau: *B*, St. Bathans Range; *H*, Hawkdun Range; *I*, Mount Ida: *K*, Kakanui Range; *S*, Shag Valley and River; *Cl*, Clutha River.

movements (*e.g.*, the Aorere, Takaka, Wairau, Awatere, Waitaki, and Taieri), while most of the other rivers are closely related to these movements, considerable portions of their courses being of simple consequent origin.

Fault Valleys and Fault-line Valleys.—Though a consequent stream may be guided by, and may excavate a valley in, a graben

or a fault-angle depression, faults do not actually form true valleys. Consequent valleys, however, such as the Shag Valley, Strath Taieri, and Manuherikia Valley (fig. 161), in Central Otago, or the Hutt Valley, near Wellington, which are modified depressions formed by faulting, may be termed *fault valleys*.

The headward erosion of subsequent and resequent streams may also be guided by the shatter-belts produced by distributed* faulting, either in the cycle introduced by the deformation of which the faulting is part or in some later cycle. The valleys so formed by headward erosion along fault-lines are termed *fault-line valleys*. It makes for clearness to observe rigidly this distinction in nomenclature between "fault-line" features, whether valleys or scarps (see below), which are developed by erosion along faults, possibly long after the faulting takes place, and "fault" features, which are directly consequent on the dislocation.

The upper part of the Kaiwarra Valley, Wellington (referred to in Chapter VII), is a fault-line valley (fig. 75, *ab*). Beyond its head the continuation of the shatter-belt it follows is occupied by the fault-line valley of another stream with the same alignment.

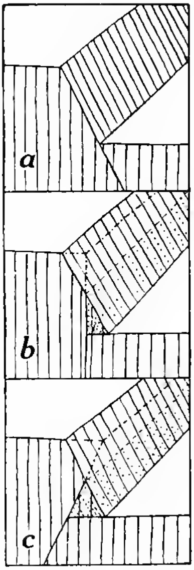


FIG. 162.—Diagram of initial fault-scarps formed by (*a*) backward-sloping, (*b*) vertical, and (*c*) overhanging faults.

Dissection of Fault-blocks.—The upper surfaces or back slopes of fault-blocks or initial block mountains may be either eroded surfaces (young, mature, or old) of an earlier cycle, or may be plains of deposition, either uplifted portions of the sea-floor or alluvial deposits.

Where the upper surfaces are initially smooth or nearly so—being in that case parts either of plains formed by deposition or of

* A *distributed* fault is one in which there is not a clean-cut break along a definite plane or curved surface of dislocation, but movement is distributed throughout a zone of considerable breadth. In this zone (*shatter-belt*) the rocks are more or less completely crushed, and many small dislocations may be traceable.

peneplains—the streams on them will be consequent on the slopes resulting from the uplift.* The surface of each high-standing block, being high above local base-levels in the neighbouring depressed areas, will be subject to rapid erosion, and will go through the usual stages of young and mature dissection.

Where, as is commonly the case in New Zealand (p. 132), the blocks consist initially of a planed undermass of resistant rocks with a relatively thin cover of weak strata, removal of the latter leads to exposure of the fossil plain on which they lie. This takes place in the early-mature stage of the cycle introduced by the block-faulting, and before erosion has obscured the outlines of the initial blocks.

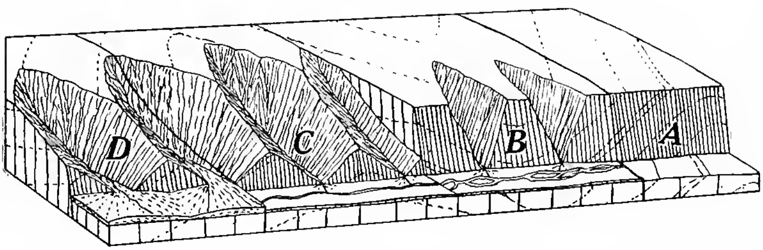


Fig. 163.—Diagram illustrating the dissection of a fault-scarp. *A*, initial form; *B*, *C*, *D*, sequential forms.

Whatever the structure, the surface will waste away eventually, if it escapes further uplift or deformation, to a low-lying peneplain.

The fault-scarp faces of fault-blocks differ so much in their initial forms from the uplifted surfaces hitherto considered that their dissection and transformation by erosion call for special description.

Dissection of Fault-scarps.—The fault-surface of which a fault-scarp is the superficial part may be vertical, may slope back towards the uplifted block, or may be overhanging. In the case of a fault-surface sloping backward at a considerable angle from the vertical, the initial topographic form may rise at the actual slope of the fault (fig. 162, *a*), but in the case of a steeper, vertical, or

* The case in which stronger initial relief is inherited from the period preceding dislocation and uplift, and influences the direction taken by streams on the block-surfaces, is not here considered, as it involves forms belonging to more than one cycle of erosion (see Chapters XVII, XVIII).

overhanging fault a great quantity of material will break off and slide away from the edge of the scarp as the earth-block rises, and so the initial topographic form will have a backward slope as in the first case, but it will now consist in its lower part of talus material (fig. 162, *b*, *c*).

The scarp will at first form a continuous wall, either straight or gently curved* (fig. 163, stage *A*), but ravines will soon be cut by streams consequent on the initial slope (stage *B*).

In the case of a simply tilted block the drainage of the whole back slope will be led away from the scarp, and so the streams forming

C. A. Cotton, photo.

FIG. 164.—Facets of the Wellington fault-scarp at Petone, N.Z.

on the scarp collect and carry away only the water actually falling upon it; but if the block-surface above the scarp is simply uplifted, and especially if it is arched by the uplift, or if it is tilted in such a way that all or part of it slopes towards the scarp, the dissecting streams of the scarp will be the lower courses of consequents of considerable size draining the upland surface. Initially they will traverse the scarp as falls or cascades. This is the origin of the

* Faults, the forms of which are well known from their occurrence in innumerable natural sections and artificial cuttings, never trace jagged, irregular, or sharply curved lines. Though they are not generally quite straight, such curvature as they exhibit is so broad and open that fault-traces are described as "simple" lines.

streams descending the north-western scarp of the Rock and Pillar Range (fig. 156), where the whole highland surface of the block slopes down towards the scarp, and a few large streams have cut

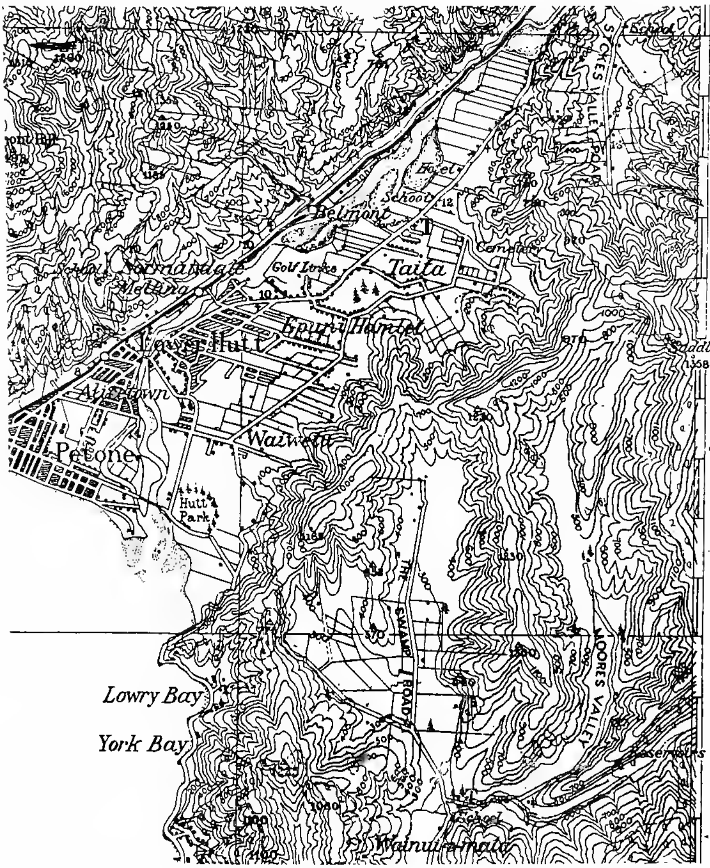


FIG. 165.—Map showing the simple line traced by the dissected fault-scarp bounding the Lower Hutt Valley on the north-western side (near Wellington, N.Z.). The map shows also the bay-head delta of the Hutt River, and the western branch of the Wainui-o-mata River, which is aggraded owing to its having been tilted headward (north-westward).

ravines far back into the range. The scarp on the opposite side of the range, facing Strath Taieri, is in strong contrast with this, being cut by no large ravines. Initially the crown of the tilted block

forming the Kakanui Range seems to have been arched, so that its crest-line divide was some distance back from the scarp descending to the Shag Valley depression (figs. 159, 161), for that scarp is dissected by streams heading back in the range and now occupying deeply-cut ravines.

With variation in the size of the drainage areas of the dissecting streams the rate of dissection of scarps may vary considerably; but even the small streams originating on the slope of a scarp have much energy, owing to their steep declivities; they become deeply incised, and work back headward into the upland block.

The dissecting streams divide the scarp into sections, and these, as the V-shaped ravines between them are opened out, are reduced to triangular *facets* bluntly truncating tapering spurs which descend from the upland above the scarp (fig. 163, stage *C*, and fig. 164). The bases of these facets of the fault-scarp are situated approximately at

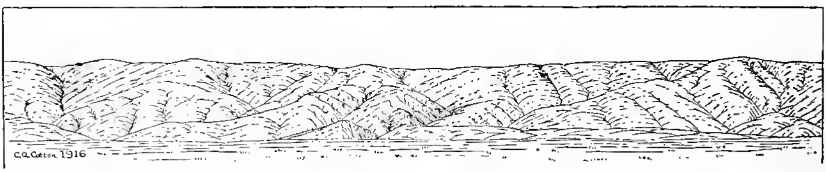


FIG. 166.—The Hawkdun fault-scarp, Central Otago, N.Z.—a maturely dissected scarp facing southward and bounding the Hawkdun Range (see fig. 161).

the fault-line, and so they trace a simple (straight or gently curved) line (fig. 165).

At this stage the dissecting ravines may be aggraded near their mouths if alluvium is accumulating in the depression at the base of the scarp (fig. 163, *D*).

When the facets have been so reduced in size by the widening of the ravines between them, and their edges have been so rounded off by soil-creep, that they no longer preserve the form of the initial scarp, the dissection of the fault-scarp is said to be mature (figs. 166–168). The ends of the spurs are still, at this stage, conspicuously ranged in line (fig. 169).

When the cycle of erosion is far advanced towards old age the spur-ends may be worn back irregularly from the fault-line, and so the even base-line is to a great extent lost, and the scarp becomes obliterated.

It has been assumed in the foregoing discussion that deformation and uplift are so rapid that they may be regarded as complete before erosion begins. It should be recognized, nevertheless, that much of the dissection of a fault-scarp may take place while movement is still in progress, either very slowly and continuously or intermittently. While this is going on, the spur-ends between the dissecting ravines are always newly emerged portions of the scarp, and, as they are being actively cut into by the ravines on both sides of them so that soil-creep cannot round off the edges, they

C. A. Cotton, photo.

FIG. 167.—Maturely dissected fault-scarp forming the western side of the Ruakokopatuna Valley, Wairarapa, N.Z. The eastern side (foreground) is a dip slope of limestone (geologically very young) which is cut off by the fault in the valley-bottom.

present conspicuous sharp-edged facets. Growing fault-scarps may thus be recognized. Many such scarps are known in western North America.

Rejuvenated Fault-scarps. — Fault-scarps affected by renewed movement after some dissection has taken place may be described as *rejuvenated.* The scarp forming the front of the Tinakori Hills, at Wellington, N.Z., and extending thence along the shore of Port Nicholson and into the Hutt Valley (the Wellington fault-scarp,

figs. 169–171), has been rejuvenated at a not-very-distant date. Recent movement is indicated by hanging (discordant) junctions made by all the smaller dissecting streams either with sea-level at their mouths, or, in the case of others, with the Tinakori Stream, which flows along the base of the south-western part of the scarp.

In the case of some maturely dissected scarps recently rejuvenated, evidence of the rejuvenation is found in low, more or less continuous scarps crossing deposits of alluvium spread in front of the earlier-formed and dissected portions.

The Recognition of Fault-scarps.—The presence of fault-scarps is such a clear indication of dislocations in the underlying rocks that their recognition becomes a matter of importance in historical geology, for a topography which includes fault-scarps preserves

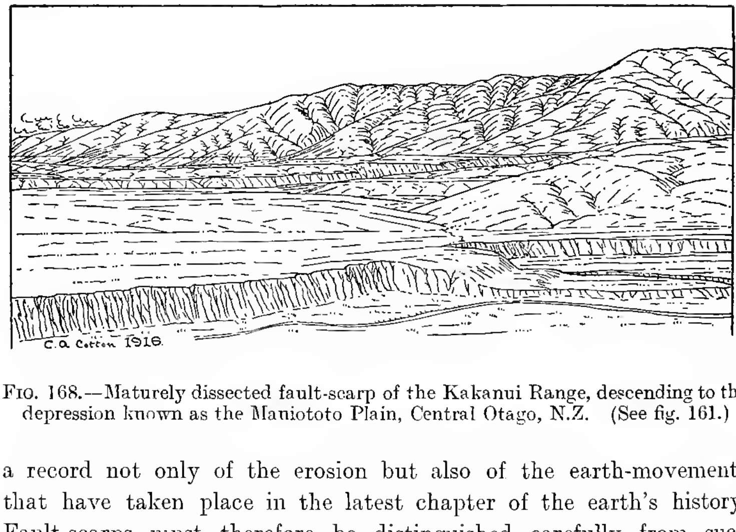


FIG. 168.—Maturely dissected fault-scarp of the Kakanui Range, descending to the depression known as the Maniototo Plain, Central Otago, N.Z. (See fig. 161.)

a record not only of the erosion but also of the earth-movements that have taken place in the latest chapter of the earth's history. Fault-scarps must therefore be distinguished carefully from such other topographic features as resemble them externally in some degree. The chief of these are—

(1.) Lines of sea-cliffs formed where marine erosion is cutting back a coast (Chapter XXVII);

(2.) The escarpments which bound mesas and cuestas;

(3.) Valley-sides in early-mature valleys which have been cut back to steep slopes by lateral stream corrasion;

(4.) The walls of glacier troughs which have been straightened and oversteepened by ice erosion (Chapter XXI).

Except in the very exceptional case of fresh fault-scarps facing each other across a narrow graben, the distinction from (3) and (4) is easily made. In the ordinary case a fault-scarp, unlike the wall of a stream-cut or glaciated valley, is not confronted by a similar scarp. In the case of a fault-angle valley, which is bounded on one side by a fault-scarp, this presents a striking contrast to the tilted surface forming the opposite side. For the Hutt Valley, near Wellington, N.Z., this contrast is brought out clearly by the contoured topographic map (fig. 165), which shows the fault-scarp forming a

C. A. Cotton, photo.

FIG. 169.—Blunt-ended spurs ranged in line, south-western end of the Wellington fault-scarp, Wellington, N.Z.

straight wall on the north-west side, while on the opposite side are deep embayments occupied by extensions of the flat valley-floor.

A useful point of distinction from a wave-cut coast is the absence at the base of a fault-scarp of an abraded rock platform, which is formed by marine erosion as a necessary accompaniment of cliff-cutting (Chapter XXVII). Such a platform is cut in the same kind of rock as that forming the cliffs. A platform, if present, at the base of a fault-scarp is, on the other hand, an

apron of waste resulting from erosion of the scarp. In the case of a young fault-scarp descending into the sea, there will be at first, as a rule, deep water close to the shore, while later there will be an accumulation of marine sediment.

At the base of the Wellington fault-scarp, where it forms the shore of Port Nicholson (fig. 172), the depth of water indicates the absence of such a platform as would be present were the

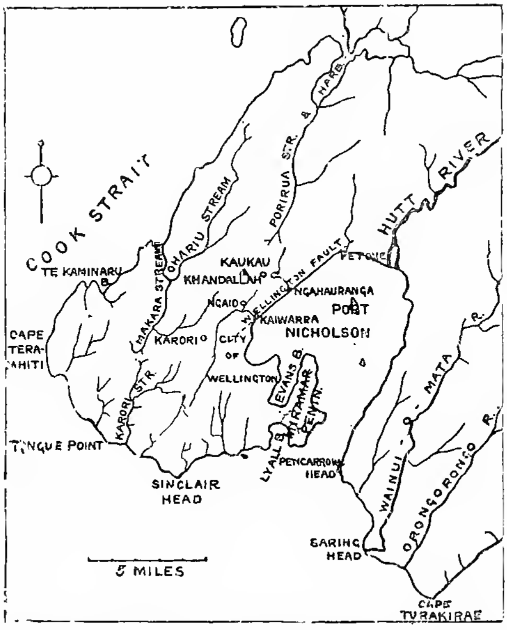


FIG. 170.—Locality-map of the Wellington Peninsula and Port Nicholson, N.Z., showing the Wellington fault-scarp.

cliffs of the scarp the work of the waves. The comparative shallowness of the water and smoothness of the bottom over the whole area of Port Nicholson show, however, that a vast quantity of sediment has been deposited in it since the former irregular land-surface occupying the area subsided along the line of the Wellington fault.

A fault-scarp can usually be distinguished from the escarpment of a mesa or cuesta by noting the geological structure. The crest or

cornice of an escarpment is formed by the outcrop of a particularly resistant stratum in a horizontal or gently inclined attitude, and in the case where the dip of the strata is appreciable the trend of an escarpment is parallel to the strike. It is, of course, quite

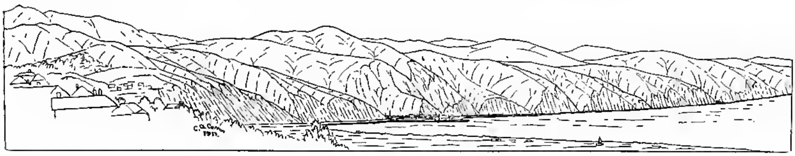


FIG. 171.—The Wellington fault-scarp, Wellington, N.Z.

possible for a series of gently inclined strata with a hard bed at the top to be dislocated by a fault, with the formation of a fault-scarp resembling an escarpment. In the case of such a simple structure, however, it is generally obvious from the geology that a fault is present. Recognizable beds—the hard band referred to above, for example—will be found at markedly different levels on opposite sides of the dislocation.

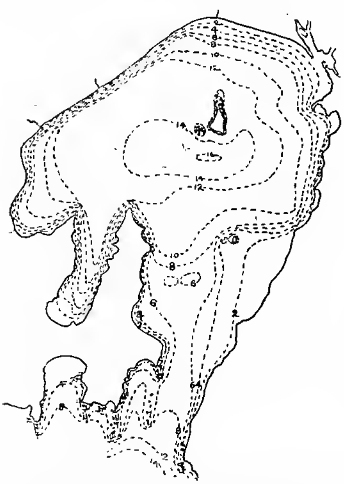


FIG. 172.—Port Nicholson, N.Z., showing contour of the bottom. Depths in fathoms.

As a general rule, there is no correspondence between the trend of a scarp and the strike of the strata or of the axes of folds. Thus the outcrops of inclined or folded strata generally run obliquely up the face of the scarp, as indicated in fig. 163.

The criteria for the recognition of fault-scarps may be summarized as follows: (1) The spurs, the ends of which are blunt or may be sharp-edged facets, all end in line; (2) the scarp may, and usually does, cut across the stratification; (3) the scarp is dissected by streams consequent on its slope; (4) there are no cut platforms on the slope in front of the spurs such as would be present if the blunt terminations of the spurs were wave-cut cliffs.

CHAPTER XIII.

LAND-FORMS ASSOCIATED WITH FAULTS (*continued*).

Distributed faults and fault-splinters. Monoclinal scarps. Fault-line scarps. Composite fault-scarps. The outcrops of strata displaced by faults. Earthquakes related to faults. Effects of earthquakes on topography. Earthquake rents.

Distributed Faults and Fault-splinters.—Faults are not always simple breaks. Sometimes the dislocating movement, instead of taking place along a single surface, is *distributed* throughout a zone of considerable width—a *shatter-belt*—in which the rock is separated into many differentially moving slices, and is much crushed and shattered. The scarps of such faults must be initially somewhat ill-defined, especially if the shatter-belt is wide, but when maturely dissected they will closely resemble the scarps of simple faults. Where the slices are wider, and escape complete shattering, the whole descent is broken into steps by *step faults*, which form at first separate scarps, and which leave their traces in the stage of maturity as jogs in the crest-lines of the spurs that descend from the upland block.

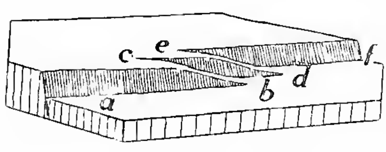


Fig. 173.—Diagram of a splintered fault dislocating a plane surface.

A simple fault, again, may branch once or many times, perhaps passing thus into a distributed fault.

A *splintered fault* differs from a distributed fault and from a branching fault in that, while the displacement on the whole fault-system remains constant throughout its length or varies constantly in one direction or the other (as might the displacement on a single simple fault), dwindling displacement on one line (such as *ab*, fig. 173)

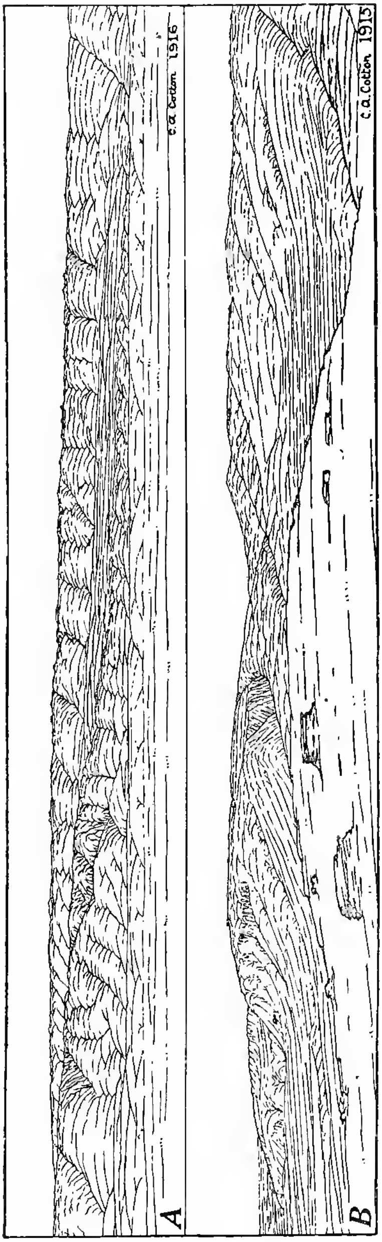


Fig. 174.—The splintered fault-scarp of Rough Ridge, Central Otago, N.Z. *A*, view looking north-west; *B*, view looking south-west up along a splinter.

is compensated by the development parallel to it of another line of fault (such as *cd*) with increasing displacement, and this may occur more than once (*ef*); so that discontinuous faults *en échelon* separating successive splinters form the complex boundary between adjacent high- and low-lying blocks. It is as though faulting had

C. A. Cotton, photo.

Fig. 175.—A splinter from the fault-scarp forming the northern wall of the Waitaki valley, N.Z. View looking northward from Duntroon.

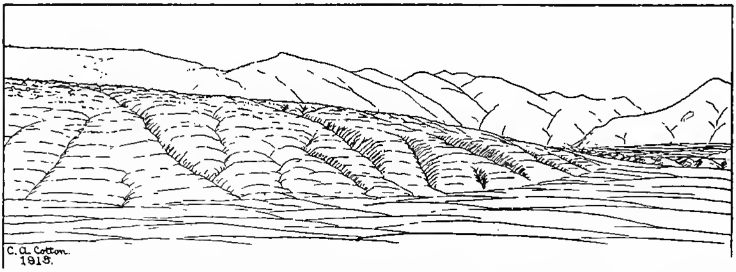


Fig. 176.—Submaturely dissected stripped fossil plain forming a monoclinal scarp near the northern end of the Blackstone Hill range, Otago, N.Z. View looking northward across Ida Valley.

followed pre-existing lines of weakness—lines of least resistance—running diagonally across the boundary between the tectonic blocks.

The eastern side of Rough Ridge, Central Otago, N.Z., is formed by the scarps of a splintered fault. Two splinters of the upland

surface descend northward to the level of the Maniototo depression (fig. 161). The first (northernmost) of these splinters is shown in fig. 174.

Another splinter breaks the continuity of the fault-scarp forming the northern side of the depression occupied by the Waitaki River (fig. 175). The township of Duntroon is opposite to it on the south side of the river. Like the Rough Ridge splinters, it shows prominently because it dislocates the fossil plain now so widely exposed in Otago and South Canterbury by the stripping-away of the covering strata.

Monoclinal Scarps.—Closely related to fault-scarps are the scarps formed by monoclinal folds, or flexures, where the surface is sharply bent down, instead of being dislocated, to form the boundary between a high-standing block and the neighbouring depression. When maturely dissected, such *monoclinal scarps*, as they may be called, will generally be indistinguishable from fault-scarps except in so far as their origin is indicated by the rock-structure. Where a fossil plain exists not far below the initial surface, remnants of it may persist on the interfluves of the scarp for a time after the cover has been stripped from it, as is the case near the northern end of the Blackstone Hill range in Central Otago (fig. 176).

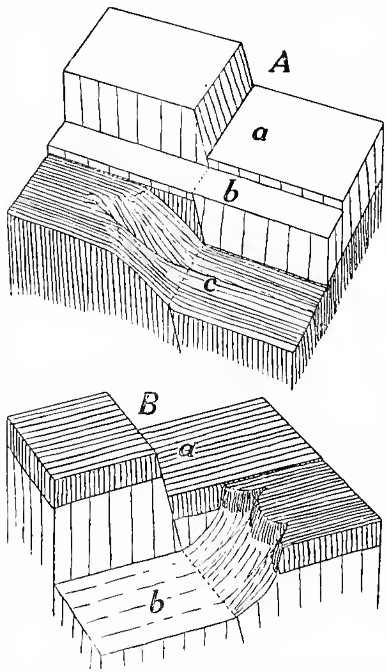


Fig. 177.—Diagrams of fault-line scarps (diagram *A*, stage *c*; diagram *B*, stage *b*). The initial fault-scarps on the same lines of fault are shown in stage *a* of each diagram.

Fault-line Scarps. — Faulting may bring together weak and resistant rocks on opposite sides of the fault-line, and removal of the weak rock by erosion leaves exposed a scarp of the more resistant rock, which persists until it also is worn down by erosion. A scarp

so formed is termed a *fault-line scarp* (Davis). Frequently fault-line scarps are exposed by the erosion following a regional uplift that takes place long after the formation of the faults, and long after the true fault-scarps marking the initial breaks at the surface have been obliterated by erosion.

Fault-line scarps are of two kinds, *resequent* and *obsequent*, according as they face in the same direction as the initial fault-scarp on the same line of fault or in the opposite direction. Thus a resequent fault-line scarp (fig. 177, *A*) faces, or descends towards, the structurally depressed (downthrown) side of the fault, while an obsequent scarp (fig. 177, *B*) descends towards the structurally uplifted (upthrown) side.

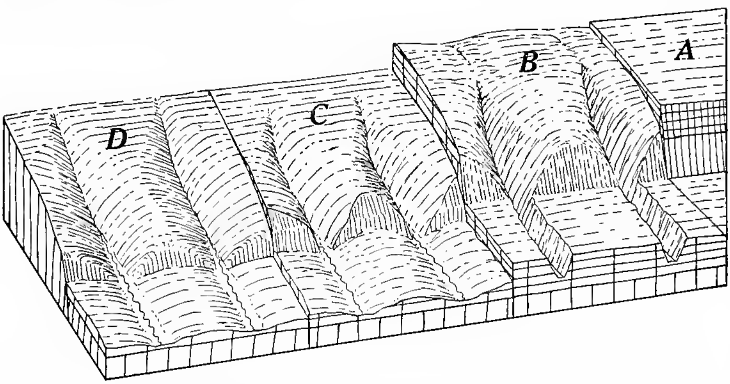


Fig. 178.—Diagram of the development of a composite fault-scarp, in its upper part a fault-scarp and in its lower part a fault-line scarp.

Resequent fault-line scarps are perhaps commoner than the obsequent variety, since it is true in a general way that the more deeply buried rocks, being older and having been subjected to greater pressure than those above them, are harder and more resistant to erosion. Exceptions to this general rule are, however, quite common. Quartzite, for example, may be found overlying limestone, which will always remain a weak rock as compared with quartzite; or older, more indurated rocks may overlie younger and weaker rocks as a result of earth-movements.

A condition that may lead to the formation of an obsequent scarp even in a single cycle of erosion is the occurrence of a sheet of volcanic lava (a hard and resistant rock) overlying soft material.

Faulting will produce a scarp—a fault-scarp—facing towards the downthrown side; but when the lava on the high side has been worn off the faulted continuation of it at a lower level on the other side may still survive and determine an obsequent fault-line scarp. This condition is illustrated in fig. 177, *B*, which should be compared with diagram *A* of the same figure, representing the development of a resequent scarp. In the latter the strip *b* represents a stage of erosion at which all traces of the fault-scarp have been obliterated; if this has occurred the change to stage *c*, in which the fault-line scarp appears, cannot take place until a general uplift of the region makes renewed erosion possible.

C. A. Cotton, photo.

FIG. 179.—An eastward-facing scarp near the southern end of the Hunter's Hills, Waimate, South Canterbury, N.Z., which is a composite fault-scarp, or (being of no great heigbt) possibly entirely a fault-line scarp.

Composite Fault-scarps. — In New Zealand the majority of the scarps generally described as fault-scarps (for example, all those referred to in the preceding chapter, with the single exception of the Wellington fault-scarp) have had a certain amount of weak rock removed by erosion along the base since faulting took place, by which erosion a portion of the fault-surface has been exposed that did not form part of the initial fault-scarp. It is clear that such scarps are in part fault-line scarps; and it is not essential, in this connection, to know whether the erosion took place in the cycle introduced by the faulting movements or later, when erosion may have been stimulated by a smaller but general uplift.

In general, however, such scarps as they exist at present are considerably higher than the probable thickness of soft material removed from the downthrow side of the faults. They must, therefore, be true fault-scarps in their upper parts. The fact that they are neither entirely fault-scarps nor entirely fault-line scarps may be indicated by calling them *composite fault-scarps* (91). Fig. 178 shows diagrammatically the development of a composite fault-scarp (stages *C* and *D*) from a simple fault-scarp (*A* and *B*).

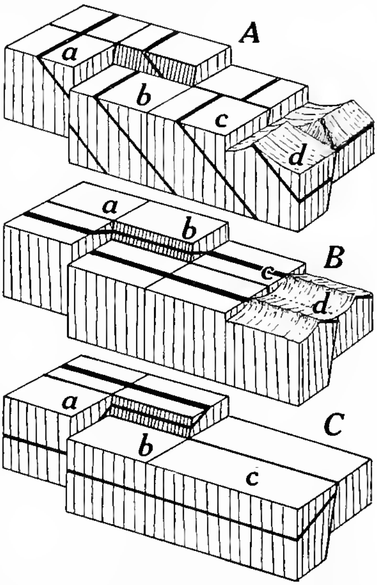


Fig. 180. — Diagrams showing displacement of strata by faulting. *A*, effect of a transverse fault ; *B* and *C*, effects of strike faults. In each diagram *a* represents the stage before faulting takes place ; *b*, the stage immediately after faulting ; *c*, the outcrops if the surface is reduced to the same level on each side of the fault ; and, in diagrams *A* and *B*, *d* shows relief etched out by subsequent erosion.

Seeing that stripping of the lower part of the exposed fault-surface need not take place until long after the formation of the fault, giving time in the meanwhile for mature dissection of the fault - scarp portion, composite fault-scarps may resemble fault-scarps rejuvenated by renewed movement. The scarp shown in fig. 179, for example, has in its almost continuous, wall - like form all the appearance of youth, resulting really from the recent exposure by erosion of at least the lower part of the scarp, following a general uplift which occurred long after that accompanying the faulting.

The Outcrops of Strata displaced by Faults.—The effects of ancient faults in displacing outcrops are frequently made apparent by erosion, especially where strong ridge-making strata are dislocated. It is unnecessary in studying these effects to take into consideration the transformation through which the initial fault-scarps passed. The faults may be assumed to be much more ancient than the topography—as, indeed, the majority of known faults are.

Faults dislocating stratified formations may be divided into two classes according as they are transverse or parallel to the strike. The latter are called *strike faults*, while the former may be termed *transverse faults*.

In some faults the movement is horizontal and the effects on topography are simple. Ancient faults with a horizontal movement parallel with the strike do not affect topography, while transverse faults in which the movement is purely horizontal simply dislocate outcrops and strike ridges to the extent of the movement. More often there is either no horizontal movement along the fault-line, or movement in that direction is subsidiary to that which has taken place in a direction up or down the fault-surface. This is the class of faults which when first formed produce conspicuous fault-scarps at the surface, and which also determine the positions of the most prominent fault-line scarps.

When erosion has reduced the dislocated portions of the outcrop of a stratum on opposite sides of a transverse fault of this kind to a common level (fig. 180, *A*, stage *c*), they are not, as a rule, in the same straight line, but one is offset relatively to the other to a distance depending upon both the amount of displacement on the fault and the angle of dip of the stratum, the offset being greater in the case of a gently dipping stratum than in the case of one that is steeply inclined. The direction of offset clearly depends upon the direction of dip of the stratum and upon the direction of relative movement on the fault.

On the dislocated ends of ridge-making strata, when the surface is in that stage of erosion at which these stand out in relief, fault-line scarps, both resequent and obsequent, are developed (fig. 180, *A*, block *d*).

Strike faults, while not causing offsets in outcrops, produce either repetition or, on the other hand, complete suppression of certain outcrops (fig. 180, *B* and *C*). Where the outcrop of a ridge-making stratum is repeated many times by a number of parallel faults a striking topographic effect is produced as ridges are etched out by erosion (block *d* of diagram *B*). Some repetition by faulting of ridge-making formations occurs at the head of the Ure River, east of the northern end of the Kaikoura Mountains, N.Z.

Earthquakes related to Faults.—The majority of earthquakes result from movements along faults. Such movements do not go on continuously, but take place rather as a series of jerks.

Where an earth-block is being uplifted, for example, the uplifting force is apparently applied continuously, and the stress accumulates until it is relieved by a sudden small displacement. The block may be arched upward while the stress accumulates, and resume its original shape when the stress is relieved. When actual movement on a fault takes place a disturbance is propagated through the earth to a great distance. This is an earthquake. The disturbance consists of waves of vibration, which are propagated owing to the elasticity of the rocks. Some of the waves follow direct paths through the earth, while others are carried by the rocks near the surface and so pass around the periphery.

W. A. McKay, photo.

Fig. 181.—Fence offset by a horizontal movement of the ground to the east (relatively) on the north side of a line of dislocation trending nearly east and west, Glenwye, Hope Valley, Amuri district, N.Z.

The great earthquake in California in 1906 was caused by a horizontal movement of several feet along a line of fracture hundreds of miles in length. In New Zealand a similar movement, amounting to 8 ft., which caused dislocation and displacement of fences (fig. 181), has been traced for several miles along a more ancient fault-line parallel to and close to the Hope River, a tributary of the Waiau,* and this movement seems to have

* A. McKay, *Rep. Geol. Explor. dur. 1888–89*, pp. 9–10, 1890; description repeated in 57, p. 28.

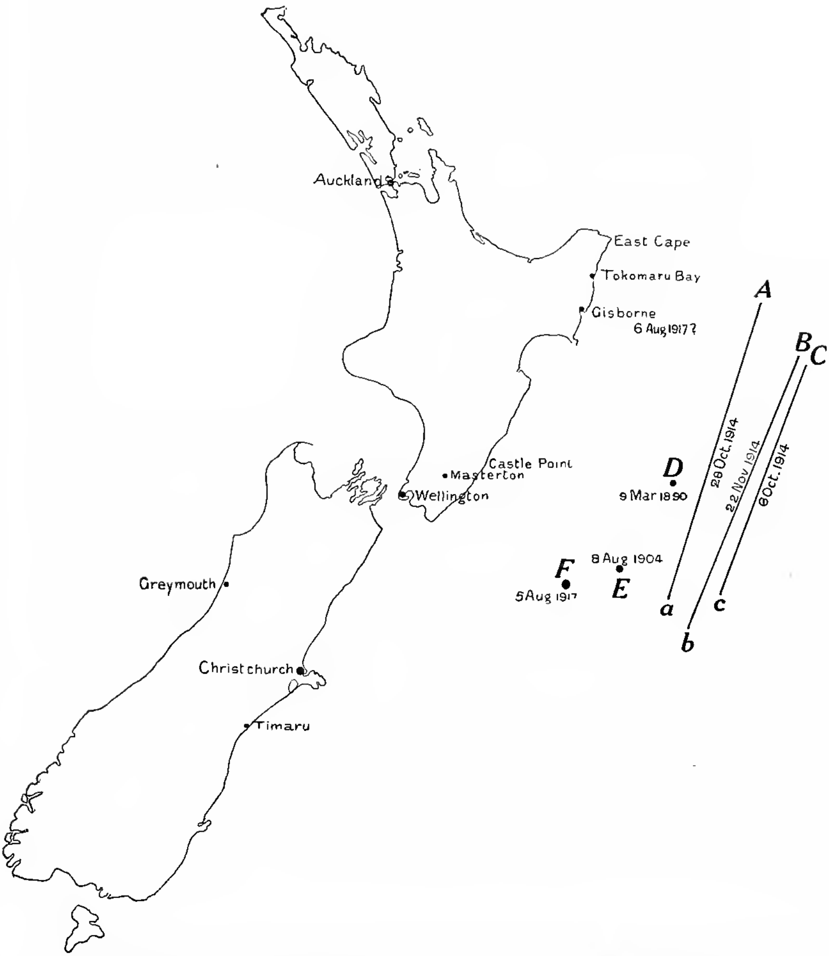


FIG 182.—Map showing some earthquake origins east of New Zealand. The origins of these earthquakes in 1914 were lines, and "it is quite possible that better records would have made the three lines *Aa*, *Bb*, and *Cc* coincide" (Hogben). (After Hogben.)

been the cause of a great earthquake in 1888. Other earthquakes, notably some in Japan, are known to have resulted from vertical movements. Most of the earthquakes felt recently in New Zealand have been caused by earth-movements of some kind beneath the sea several hundred miles to the east, where it is possible that a great submarine fault-scarp is in course of formation (fig. 182).

Effects of Earthquakes on Topography.—In addition to scarps at the surface which are the result of the earth-movements that produce earthquakes, there are features resulting from the earthquakes themselves, where they disturb loose and inelastic material. Large landslips may result, which leave great scars of

W. A. McKay, photo.

FIG. 183.—Earthquake rent tracing the line of outcrop of a great fault which bounds on the south-eastern side the tectonic block forming the Seaward Kaikoura Mountains, Lottery Creek, Amuri district, N.Z.

typical form on hillsides, or there may be only small slips leaving either gaping fissures or low scarps which may be mistaken for fault-scarps. They will be found, however, only in loose material such as alluvium, and will be short and curved, or may be grouped in an irregular network, thus differing from fault-scarps, which continue in nearly straight lines across the country perhaps for many miles, traversing resistant as well as weak rocks. Funnel-shaped pits, like small craters, are also produced by sudden ejection of water

caused by the slipping and subsidence of loose superficial material. Abundant earthquake effects of these various kinds were produced by the great earthquakes which occurred in 1888 and 1901 in the north-eastern part of the South Island of New Zealand (McKay, 57).

Earthquake Rents. — Following the lines of outcrop of faults along the fault-scarp fronts of mountain blocks there are in the north-eastern part of the South Island of New Zealand some continuous narrow benches, 20 ft. or 30 ft. wide, passing in places into shallow trenches (fig. 183), which are given the name "earthquake rents" (McKay, 57). They trace straight or nearly straight lines, ascend and descend as they cross spurs and ravines, and continue for many miles. One, for example, along the north-western side of the tectonic depression forming the Awatere Valley is traceable for about fifty miles. They are obviously not fault-scarps recently rejuvenated by renewed faulting, such as are found in similar positions in western North America; nor are they the traces of faults along which horizontal movement has recently taken place (p. 173), for such faults crossing spurs cause the formation of scarps facing in opposite directions on opposite sides of the spurs. They may have been developed along the fault-lines by erosion aided by a slight gaping of the ancient fault-fissures due to disturbance by modern earthquakes resulting from differential movement of neighbouring fault-blocks (84, p. 237); but the occasional trench-like form strongly suggests recent movement on the faults in the reverse direction from that which initiated the great fault-scarps above them.

As it is on record that the formation of some of these features —more probably a rejuvenation due to reopening of the fissures— was observed to be associated with the great earthquake of 1848 (56, p. 89), the name "earthquake rents," which is generally applied to them, seems appropriate.

CHAPTER XIV.

BLOCK MOUNTAINS AND RELATED FEATURES IN NEW ZEALAND.

The mountains of New Zealand. Examples from Central Otago. Examples from northern Nelson. The mountains of the North Island.

The Mountains of New Zealand.—Formerly the mountains of New Zealand—that is to say, the Southern Alps and other chains formed of the older rocks—were regarded as fold mountains (p. 249) still undergoing erosion in the cycle introduced by the uplift accompanying the folding; though the great length of the period that has elapsed since the folding is sufficient in itself to render this explanation extremely doubtful. In recent years it has become apparent that the original fold mountains were more or less completely destroyed by erosion and that their site was largely covered by younger rocks prior to uplifts which initiated the sculpture of the present ranges, and, further, that the later uplifts, to which the present relief is due, were differential.* The features to which these *orogenic* (mountain-making) movements gave rise are still, in some parts of New Zealand, well-preserved block mountains, and practically everywhere the tectonic nature of the relief is still recognizable, New Zealand may, in fact, be described as a concourse of earth-blocks, the highest of which lie on the north-east and south-west axis of the land-mass.

The initial surfaces of the blocks over a large part of the region were portions not of a previously eroded land-surface, but of a plain of deposition, mainly marine. A weak sedimentary cover, largely a marine but partly a fluviatile deposit, lay (and in places still lies)

* See 89 and 91.

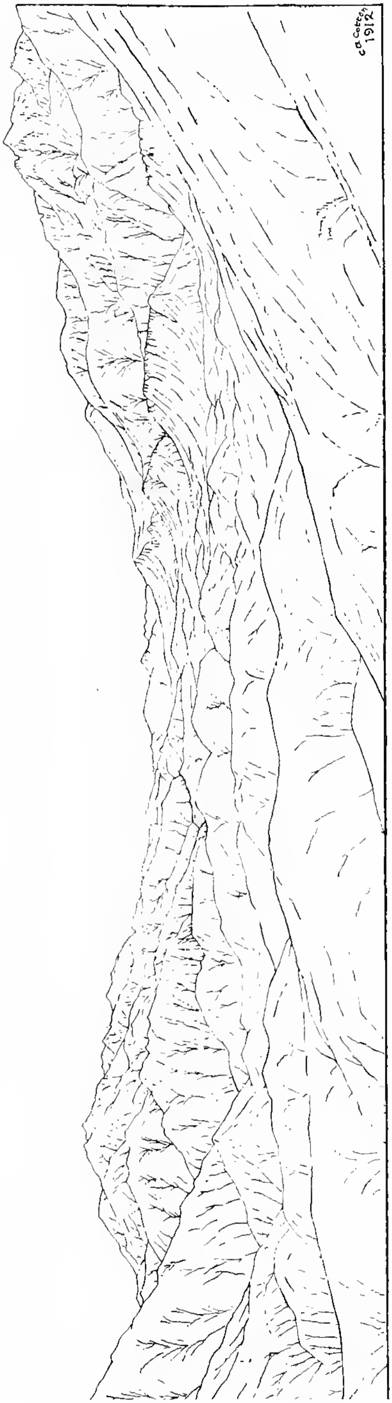


FIG. 184.—View looking south-westward up the valley of the Clarence River, N.Z., between the dissected back slope of the Seaward Kaikoura block, on the left, and the scarp of the Kaikoura block, on the right. The homoclinal ridge along the base of the latter marks the outcrop of the most resistant bed of the cover preserved in the tectonic depression between the ranges (figs. 85, 135).

C. A. Cotton, photo.

FIG. 185.—Full-face view of the dissected fault-scarp of the Kaikoura mountain block, showing Mount Tapuaenuku, the highest peak of the Kaikoura Range, N.Z.

J. Park, photo

FIG. 186.—View looking across the Manuherikia Valley, N.Z., part of the Central Otago chain of depressions. An uplifted block, forming the Dunstan Mountains, is seen in the distance.

upon the planed surface of a more resistant undermass of complex structure.

In the deformation that produced the initial forms from which the main topographic features have been carved there was a considerable development of strong warping as well as faulting, while in some places the covering strata were compressed into folds. The uplifted blocks are not bodily uplifted with fault-boundaries on all sides, but are in part anticlinal, and the depressions are in part synclinal. The surfaces of these structural units or blocks in the initial stage were in part horizontal flat areas (high- or low-lying), while there were some flat back slopes or areas of surface with a gentle and nearly uniform slope, and some fold surfaces or areas of steeper slope not necessarily so uniform. The steep surfaces marking the boundaries between upland and lowland blocks were in some cases fault-scarps, but in other cases, where monoclinal folds replaced faults, they might be termed monoclinal scarps. A system of consequent drainage was established, and it is to this deformation of very modern date (geologically speaking) that the establishment of the majority of the New Zealand rivers may be assigned.

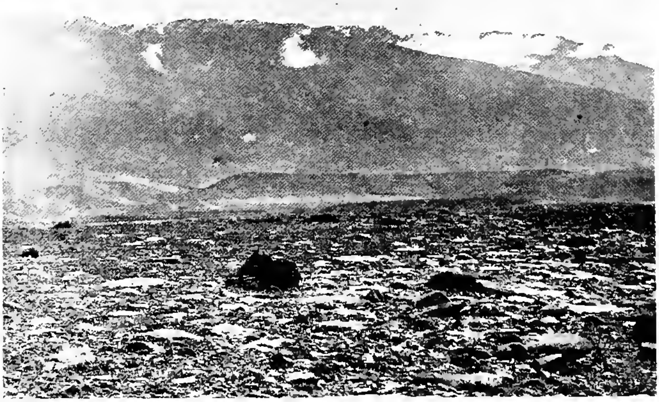
In the period during which the concourse of earth-blocks forming New Zealand has been subjected to subaerial erosion, the covering beds, except where they are particularly resistant, have been removed from the upland blocks. They still survive, however, on low-lying blocks, generally near the coasts, but in a few places inland in intermont basins (formed by low-lying surrounded by higher blocks).

Where the cover is removed the fossil plain upon which it lay is either stripped and exposed as horizontal or gently tilted plateaux which are but little dissected, as in Otago, South Canterbury, and northern Nelson (figs. 140–149); or the undermass is maturely dissected, as, for example, in the main range of the Southern Alps, over the greater part of the Rimutaka, Tararua, and Ruahine Ranges, or in the Kaikoura and Seaward Kaikoura Mountains, though in the latter case the tilted-block origin is still apparent in the broad outlines of the mountain-masses (fig. 184, 185).

The covering strata on the low-lying blocks have been maturely dissected, and over large areas almost completely planed, by erosion since the deformation (pp. 129–30), and, as a rule, much of the present relief in the districts still covered by these rocks is due to

C. A. Cotton, photo.

FIG. 187.—View looking northward across the Ida Valley, N.Z., part of the Central Otago chain of depressions.



C. A. Cotton, photo.

FIG. 188.—View looking across the Cromwell depression, N.Z. (part of the Upper Clutha chain of depressions), at the scarp of the Mount Pisa uplifted block to the west.

renewed erosion brought about by recent movements of uplift, generally regular and affecting considerable areas, so that, as far as a particular district is concerned, they may be classed as regional.

The fault-scarp boundaries between the high- and low-lying blocks are, as a rule, dissected to the mature stage. Rejuvenation of the dissected scarps by renewal of movement, with the formation of new and continuous scarps at the base or the production of sharp facets on spur-ends, has taken place very rarely.

Examples from Central Otago.—It is perhaps in Central Otago that the structure and the history of the earth-movement are best displayed by the topography. The landscape is a mosaic of blocks. The mountains are block mountains, and might be described as parts of a broken plateau raised to various levels and separated by large and small depressions formed by lower-lying blocks. One group of the lower-lying blocks (fig. 161) determines a chain of basins, which have been known in the past as "old lake-basins," though it is not clear that they have ever been occupied by lakes. This is the chain of lowlands followed by the Otago Central Railway. Parts of it are shown in figs. 186 and 187.

Another and rather less extensive chain of depressions is occupied by the upper Clutha and its tributaries, and may be called the Upper Clutha chain (fig. 188).

The depressions occupied by large lakes farther west—*e.g.*, Wakatipu and Te Anau—were perhaps initially of the same nature, but they have been profoundly modified by glacial erosion. In Central Otago the covering strata are largely of terrestrial origin, and have been preserved over considerable areas on the low-lying blocks in the depressions, though only a few remnants survive on the higher blocks. The configuration of the higher blocks shows very clearly the nature of the deformation, as extensive areas of the fossil plain that formed the floor on which the cover lay are preserved. The manner in which the fossil plain is warped and dislocated is clearly seen. The majority of the Central Otago blocks are elongated, trending north-east and south-west, and are more or less tilted towards the north-west. These blocks slope down gently to their north-eastern ends to merge with the Central Otago chain of depressions previously referred to, which forms a composite fault-angle depression at the base of the fault-scarps

bounding a group of high blocks forming the northern highland of Otago.

Examples from Northern Nelson.—Large tectonic features abound in the provincial districts of Marlborough and Nelson; in fact, the whole surface there displays evidence of development of the relief from great earth-blocks in various attitudes. The Kaikoura and Seaward Kaikoura Mountains have already been referred

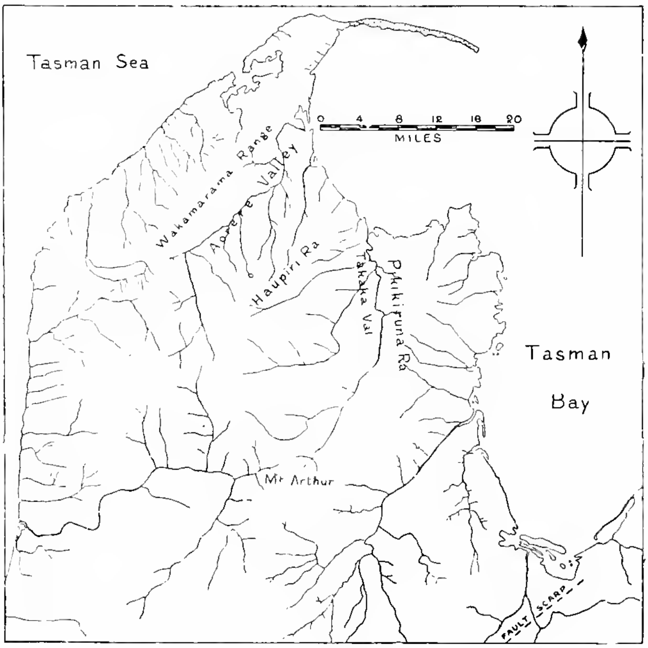


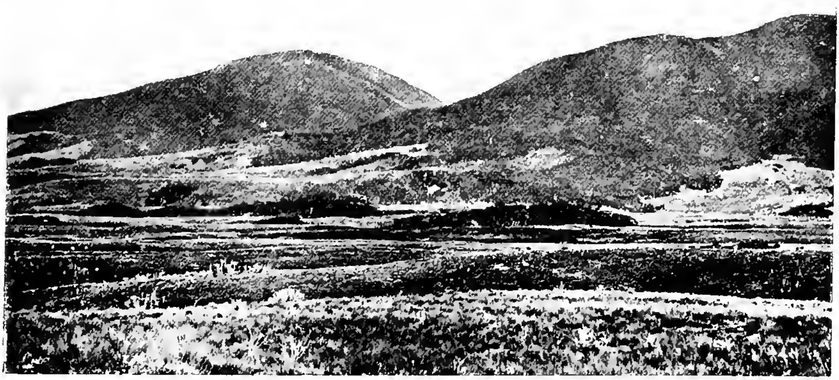
Fig. 189.—Locality map of northern Nelson, N.Z.

to. The valleys of the Awatere and Wairau Rivers clearly mark the position of depressed blocks—great triangular areas of subsidence. In northern Nelson (fig. 189) the shape of the uplifted blocks is unusually well preserved on account of the highly resistant nature of the prevailing rocks of the undermass in that district.

Tasman Bay, with the depression at its head, marks the site of a low-lying earth-block, and in the north-western corner of the

C. A. Cotton, photo.

Fig. 190.—The Gouland Downs Plateau (Nelson, N.Z.) in the foreground, separated by a fault-scarp (composite) from a higher, flat-topped block to the north.



C. A. Cotton, photo.

Fig. 191.—The Gouland Downs Plateau (Nelson, N.Z.) in the foreground, separated by a monoclinal scarp from higher country to the south-east.

South Island two fault-angle depressions, the Aorere and Takaka Valleys (see fig. 189), open out broadly towards the north-east and north, separating three composite upland blocks which, owing to diminishing throw of the boundary faults and consequent dwindling of the fault-angle depressions towards the south-west, coalesce in that direction. The north-western, or Wakamarama, block presents a fault-scarp front, but little dissected, towards the Aorere Valley, while north-westward its back slope, much dissected by consequent streams, descends towards the Tasman Sea. The depression of the Aorere Valley is continued south-westward by the plateau of the

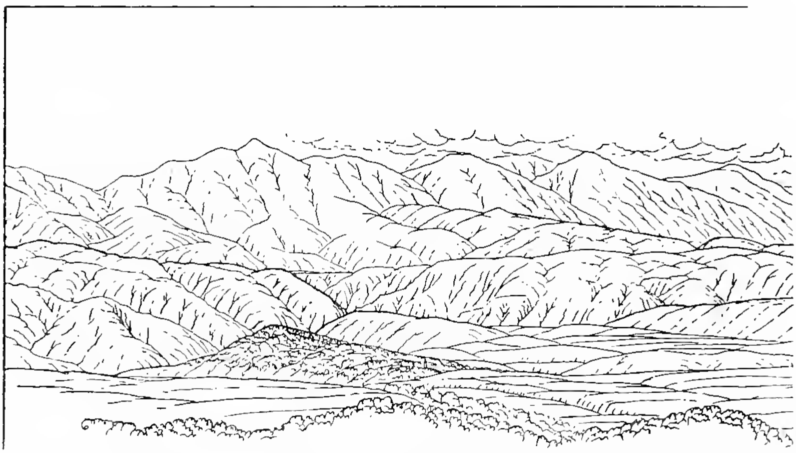
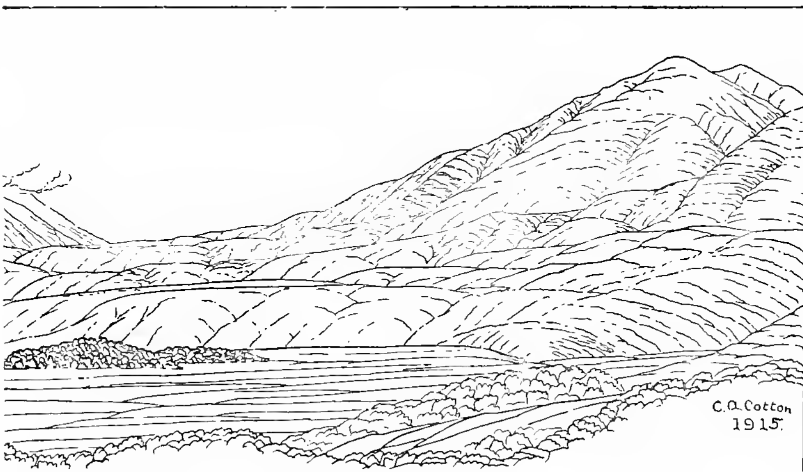


FIG. 192. — View looking north-east across the Gouland Downs Plateau and the The Wakamarama fault-scarp is seen in the

Gouland Downs (fig. 149), which, though more than 2,000 ft. above the sea, is separated by a fault-scarp on the north (fig. 190) and a monoclinal scarp on the south-east side (fig. 191) from blocks of higher country. The fault-scarp which separates the Wakamarama Range from the Aorere Valley does not continue as far as the Gouland Downs Plateau, but dies out and is replaced for some distance by warping, with the result that a peculiar structure occurs, the form of which resembles that taken by a sagging sheet of fabric supported by a string loosely stretched between two points of

support of equal height. Owing to the stripping-away of the cover from the resistant undermass this structure is revealed by the exposed fossil plain, which forms a "catenary" saddle between the Aorere Valley and the Gouland Downs Plateau (fig. 192).

The mountain-ranges of the middle, or Haupiri, block — that between the Aorere and Takaka Valleys — appear to have been carved from a mass which had initially a roughly anticlinal or domed form, its present surface descending towards the north-west, north-east, and east from heights of over 5,000 ft. at the south-western end. The block is perhaps composed throughout of a number of



"catenary" saddle which separates it from the Aorere Valley depression, Nelson, N.Z. distance in the centre. Angle of view, about 75°.

smaller or secondary blocks separated from one another by faults and flexures.

The Takaka Valley fault-angle depression is bounded on the east for twelve miles by an almost undissected fault-scarp nearly 3,000 ft. in height, with a north-and-south trend, which is the western edge of the block forming the Pikikiruna Range, and which may, therefore, be named the Pikikiruna fault-scarp (fig. 193). Strictly it is a composite fault-scarp. Fig. 154 (p. 149) shows the crest of the Pikikiruna mountain block.

The Mountains of the North Island.—In the North Island the mountain blocks from which the covering strata have been stripped occupy a much smaller proportion of the area than in the South Island, and the individual blocks seem to be larger. The most prominent highland block, or series of blocks, is that forming the Rimutaka, Tararua, Ruahine, and Kaimanawa Ranges. Along the eastern base of the Rimutaka Range there is a prominent scarp, and a broad fault-angle depression—the Wairarapa Valley—lies

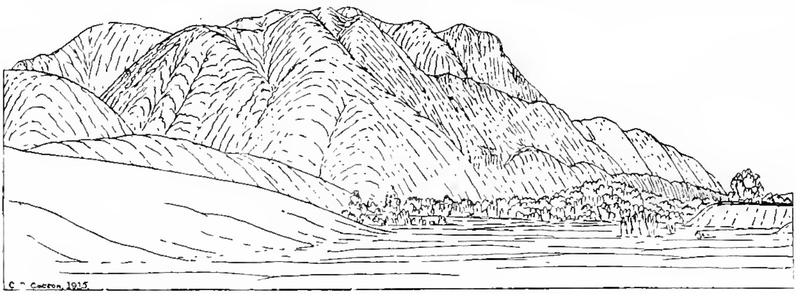


FIG. 193.—View looking south along the Pikikiruna fault-scarp, which bounds the Takaka Valley (Nelson, N.Z.) on the east. In the centre is seen a hogback of the covering strata, which are turned up along the fault.

between this scarp and the back slope of a block, or group of blocks, forming the east-coast ranges.

A prominent tectonic block forms the Thames-Coromandel Peninsula and the upland area that forms its continuation to the south, and this block is separated by a fault-scarp from a depressed block —in part, apparently, a graben—that forms the Thames Estuary and the Hauraki Plains.

CHAPTER XV.

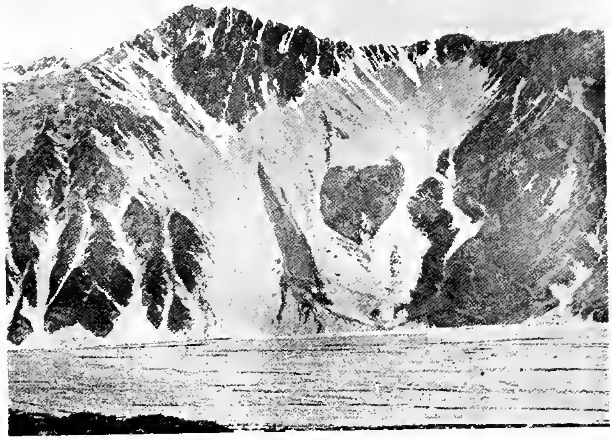
LAND-FORMS BUILT OF WASTE IN THE COURSE OF THE NORMAL CYCLE.

Terrestrial deposits. Talus slopes. The waste-mantle on graded slopes. Alluvial deposits. Aggraded valley-floors. Braided channels of aggrading rivers. Alluvial fans. Piedmont alluvial plains. Deltas. Delta-plains. Instability of river-courses on deltas and aggraded plains. The structure of alluvial deposits.

Terrestrial Deposits. — The ultimate resting-place of the bulk of the waste derived from the land is in the sea. Deposits formed along the courses of streams, perhaps in hollows of the initial surface, are, as a rule, less permanent than marine deposits, for if far above base-level they will be cut away in the later stages of the cycle. They represent only pauses in the discontinuous seaward movement of the waste. Such deposits may, however, be preserved for an indefinite period if they are lowered by earth-movements below sea-level. In that case they are buried by marine deposits, and their lowly position preserves them from erosion until they chance to be again uplifted.

Even the shorter-lived terrestrial deposits above base-level may survive for a considerable fraction of a cycle of erosion, and while they last their surfaces form important topographic features. Among forms resulting from accumulation may be placed the more or less continuous mantle of surface waste, creeping and slipping downhill and thus smoothing out irregularities of the surface, accumulating so as to fill up re-entrants, and flowing around the more prominent rock outcrops until eventually these disappear and the waste-mantle becomes continuous, the slope being then graded.

Talus Slopes.—*Talus slopes*, or *screes* (see fig. 17), are a phase of the waste-mantle at the early, discontinuous stage. A talus slope is formed by the actual flow of a stream of newly broken



C. A. Cotton, photo.

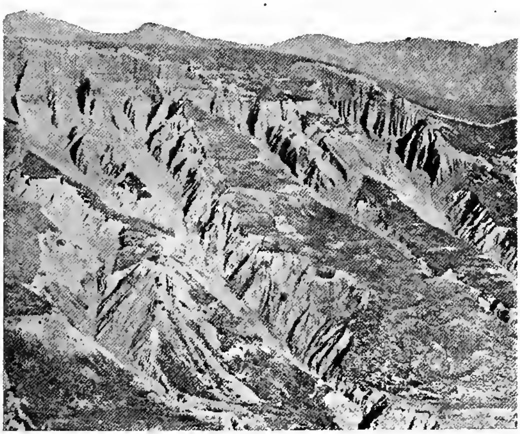
FIG. 194.—Talus slopes (the smooth grey areas) on a mountain-side. View across the Hooker Valley from the Hermitage, Canterbury, N.Z.

C. A. Cotton, photo.

FIG 195.—Talus slopes at the base of wave-cut cliffs from which the sea has retreated a short distance owing to uplift of the land, near Wellington, N.Z.

rock-fragments which, being unworn, are necessarily angular unless derived from a pre-existing accumulation of gravel. The surface slopes at the angle of repose, and the talus has accumulated as layers parallel with the present surface. A distinct stratification is not generally present, however, as the material is generally coarse and fragments of the different kinds of rock that may be present are mixed throughout.

Talus slopes are common features on mountain-sides, where the fragments broken by weatheriug from the bare rocks of the peaks



R. Speight, photo.

Fig. 196.—An early stage in the destruction of a previously graded slope of a deposit of gravel by gullying and "badland" sculpture as a result of burning the protective covering of forest, Esk River, Canterbury, N.Z.

and higher slopes stream down through funnel-like gullies. The talus slopes, confined for some distance in these gullies, spread out lower down in conical shape, delivering their surplus waste eventually into streams of water in the larger valleys of gentler declivity. Talus slopes of this kind are particularly abundant in mountains the slopes of which have been "oversteepened" by the action of glaciers (Chapter XXI). There is a great development of them in the mountains of Canterbury (fig. 194), where they receive the

C. A. Cotton, photo.

Fig. 197.—Gully eroded in a previously graded surface the native vegetation on which has been interfered with by burning and the grazing of animals introduced by man, Weka Pass, Canterbury, N.Z.

C. A. Cotton, photo.

Fig. 198.—Gullying and destruction of graded slopes taking place as a result of clearing forest, near Wellington, N.Z. Aggradation is in progress in the valley below.

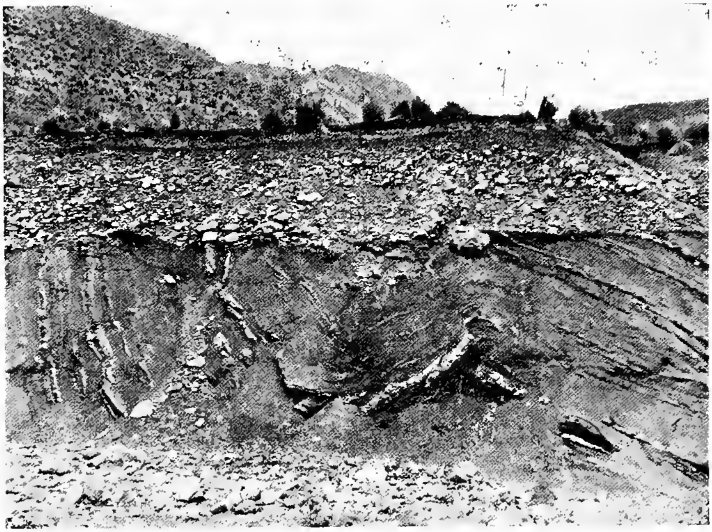
local name "shingle-slips," the term "shingle" being in this case used for the angular talus material, though it is generally used for water-worn gravel, more especially that found on beaches.

Besides being common features of mountain-sides, talus slopes occur fringing cliffs, whatever the origin of the cliffs, provided that the rate of removal of material from the base of the cliffs does not exceed the rate of supply from weathering of the bare rocks above. In many places around the southern end of the North Island of New Zealand the sea-cliffs formed by wave-action are not at present being undercut by the sea, for a small movement of uplift of the land has very recently taken place, which has caused the shore-line to retreat from the cliff-base. Since this event talus slopes have been formed which are now prominent features (fig. 195). They are accumulations of material which would, but for the uplift, have been washed away by the sea as fast as it came down.

The angular fragments of more or less fresh rock forming the surface of a talus slope are not, as a rule, exposed long enough to weathering to allow of the formation of a covering of soil, for rock-fragments are streaming down from above, and so the surface layers are either quickly covered over as the talus grows thicker, or else the surface material continues to stream down as it is swept away by running water at the toe of the slope. Vegetation is therefore almost entirely absent from talus slopes.

The Waste-mantle on Graded Slopes. — On more gentle, graded slopes, where the waste-mantle consists of weathered material not streaming but slowly creeping downhill, vegetation flourishes. In fact, the stability of slopes depends largely on the natural vegetation. A slope may be steep and yet the soil may be so bound and protected by the vegetation, forest perhaps, that streaming is prevented and only creep permitted, so that there is a state of balance between the rate of removal of waste and the rate of supply by weathering.

When the natural vegetation, whether forest or grass, is interfered with, erosion, with the formation of deep gullies, may begin on a previously graded surface (figs. 196, 197). Clearing or burning the forest from any steep slopes in New Zealand (and also in other countries) has seriously disturbed the state of balance between the rates of weathering and of removal of waste. Removal of weathered waste becomes more rapid owing to exposure to



C. A. Cotton, photo.

FIG. 199.—Natural section showing the veneer of alluvium on a flood-plain. The stream that spread the alluvium has since cut a trench through it. Swale Stream, Clarence Valley, N.Z.

R. Speight, photo.

FIG. 200.—The aggraded valley of the upper Rangitata, with the Potts River (in flood) flowing in braided channels in the foreground, Canterbury, N.Z.

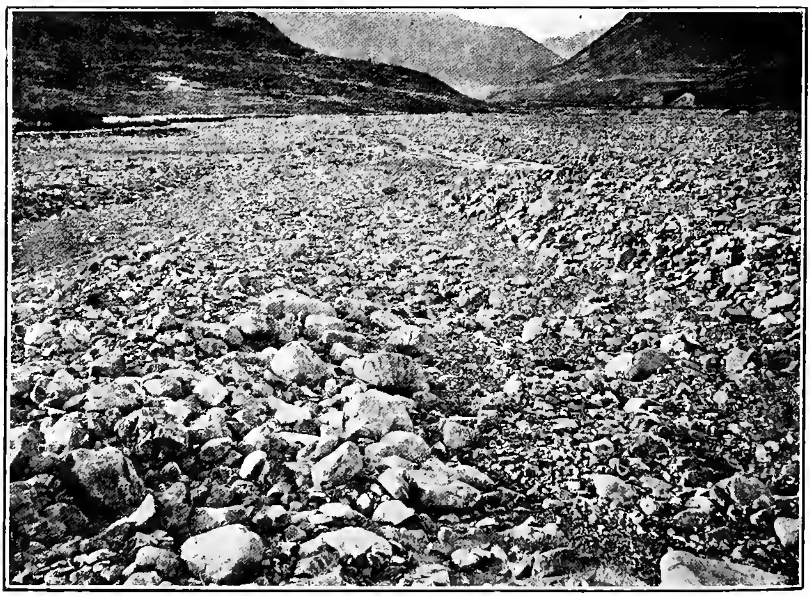
rain-wash and to the absence of binding roots. The soil may be entirely removed, actual streaming of loose waste may begin, and the formerly soil-covered hillside may become a loose talus slope, broken generally by ragged outcrops of exposed rock (fig. 198).

Not only are hill-slopes thus rendered barren, but neighbouring valleys are also injured. The supply of waste to streams is increased to such an extent that they become overloaded and are caused to aggrade, filling up and reducing the capacity of their channels so that they become subject to frequent floods, and also depositing coarse gravel over what may have been very fertile valley-plains. The tendency to flood is also increased by a rise in the proportion of the precipitation that runs off immediately from the surface, stream-volumes thus fluctuating much more than formerly. This is owing to loss from the hill-slopes of the waste-mantle, which has, when present, a great capacity for absorbing rain-water and storing it as ground-water. It thus appears that there is a critical slope below which it is safe and above which it is a great mistake to clear forest from hillsides. This critical slope varies with the nature of the rocks and also with the climate. It may be discovered in any particular district only by experience. Good turf protects slopes nearly though not quite as well as forest, and in many parts of New Zealand steep slopes have been cleared and grassed successfully, the grass becoming established before the binding effect of tree-roots is lost through their decay. In some parts of the world great quantities of soil have been lost and large areas rendered barren by cultivation of slopes that are too steep, the critical slope for tillage being much gentler than for grass-land. In some countries slopes are terraced at great expense to save the soil, and some loss may be obviated by contour ploughing. Where new gullies are formed by rain-wash their further development may sometimes be checked by choking them with stones and brushwood.

Alluvial Deposits.—A flood-plain, or valley-plain, developed as previously explained, is the flat surface of an accumulation of alluvium on the valley-floor, the depth of the alluvium being not less than the depth of the channel of the river, which has planed off the bed-rock as a floor for the alluvium (fig. 199). The superficial layer of fine silt deposited during floods is thickest close to the sides of the regular stream-channel, where deposition takes place as soon

C. A. Cotton, photo.

FIG. 201.—Braided channels of the Clarence River, Marlborough, N.Z., near the river-mouth.



C. E. Foweraker, photo.

FIG. 202.—Recently abandoned channel in the bed of an aggrading river, Cass River, Canterbury, N.Z.

as the water loses velocity owing to spreading over the flood-plain. Hence the cross-profile of the valley-plain is not quite a straight line. The highest parts are near the river-banks, and from these there are very gentle slopes away from the river. In the case of large graded rivers, such as the Mississippi, these cross-valley slopes are much steeper than the very gentle down-valley slope of the river and its flood-plain. As they act in the same way as artificial walls (levees) in confining the river to its ordinary channel during floods, the low ridges of alluvium along the river-banks are termed *natural levees.*

Aggraded Valley-floors.—Where a river has aggraded its valley the deposit of alluvium forming the valley-floor is thicker than the depth of the stream-channel, the thickness being perhaps hundreds or even thousands of feet. The causes that may lead to aggradation in a stream already graded need not yet be considered; but as examples of aggraded valleys those may be chosen in which aggradation has taken place because required to steepen slopes initially too gentle to give the streams velocities sufficient to transport their loads. The upper valleys of the large rivers of Canterbury, N.Z.—for example, the Waimakariri, Rakaia, and Rangitata—are of this kind, for there, as in many other mountainous regions, the initial forms of the valleys of the present cycle of normal erosion were the troughs excavated by glaciers during an earlier period of refrigeration. The floors of such aggraded valleys are now broad, and in a general way flat. They may be described as *aggraded valley-plains* (fig. 200). Little, if any, of their width is due to river planation, for, as the thickness of the alluvial deposit increases, the valley-floor necessarily grows wider.

Braided Channels of Aggrading Rivers.—Aggrading streams are not confined to well-defined channels, for deposition goes on in the channels, filling them up. Where a channel is thus filled the stream in it flows at a higher level than neighbouring parts of its valley-plain on the strip of alluvium it has just deposited. Such a course is obviously unstable, and the stream will sooner or later overflow at some point, scour out a passage through its low bank, and either take an entirely new course over the valley-plain or divide into two distributaries, to unite again farther down the valley. Aggrading streams repeatedly divide and subdivide in this manner, flowing in anastomosing (or *braided*) courses (fig. 200). A network of ever-changing channels without well-

defined banks occupies the valley-floor, which also is not quite horizontal in cross-profile, but gently convex.

Fine examples of braided courses are found in the aggraded valleys of the large rivers of Canterbury, referred to above. The Clarence River, Marlborough, is aggraded, and flows in braided channels, near its mouth (fig. 201), owing to the rapid increase in the length of the river due to the seaward growth of its delta (p. 207). Braided courses occur, indeed, and indicate that aggradation is in progress, in the majority of New Zealand rivers; but in many parts of the country the change from degradation to aggradation seems to have taken place very recently.

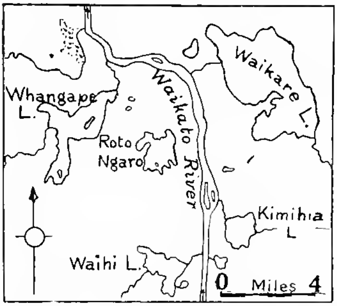


FIG. 203.—Lakes formed as a result of ponding of tributaries by alluvium deposited by the Waikato River, N.Z.

Aggraded valley-floors are often stony and infertile, as any fine silt deposits become covered over by gravel (fig. 202). Though the spaces between stream-channels may support vegetation, they are very liable to flooding.

It may happen that a tributary stream is unaffected by a change of conditions which overloads a main stream and causes it to aggrade. Aggradation raises the level of the main river at the junction—*i.e.*, raises the local base-level—and the tributary in its turn is thereby compelled to aggrade its course. Aggradation in the valley of the main river may go on so rapidly, however, that tributaries with a smaller load of waste cannot keep pace with it. They are then ponded by the alluvium of the main valley and spread out to form lakes. In New Zealand the Wairarapa Lake is thus impounded, or has at least had its level raised, by alluvial deposits spread by the Ruamahanga River across the course of the Tauherenikau (see fig. 409, Chapter XXVIII); Hatuma Lake, in the Hawke's Bay district, has been impounded in the valley of a small tributary of the Tukituki River as a result of aggradation taking place in the main river; and along the lower course of the Waikato River numerous lakes, some of them of considerable size (fig. 203), have been formed in the valleys of its tributaries, which

have spread widely over a surface of small relief as the main river deposited across their mouths its load of waste brought from the pumice-covered central volcanic district of the North Island.*

Alluvial Fans. — As rivers emerge fully loaded from eroded valleys, in which they may have been degrading, into wide depressions where the slope is so gentle that the streams are compelled to aggrade in order to prolong their graded slopes—or, in other words, to build up channels sufficiently steep to give them their needed velocity—they deposit part of their load in such a manner as to build *alluvial fans.*† The surface of a fan resembles a portion of a low cone with its apex in the mouth of the valley from which

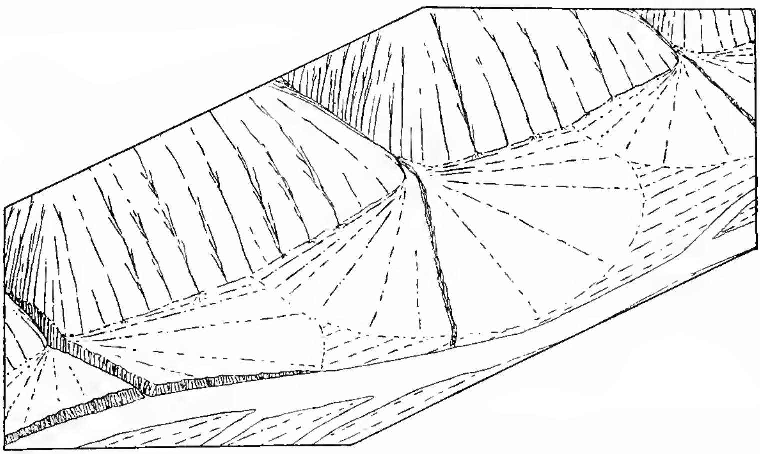


FIG. 204.—Diagram of alluvial fans built by tributaries where they enter the valley of a large river.

the fan-building stream emerges, the slopes being the same from this point down every radius of the fan. The surface of a fan is not strictly conical, for towards the head of the fan the slopes ar.

* This explanation of the formation of lakes along the course of the Waikato River was given by Dr. J. Henderson in a paper read before the Geological Section of the Wellington Philosophical Society, 15th July, 1920.

† Drew, 41, p. 448. In America the term "alluvial cone" is in use; but Gilbert has suggested that it be restricted to the steeper forms, those less steep being termed "alluvial fans." The term "fan" was used as early as 1864 in New Zealand by Haast (49, p. 20). He restricted it, however, to the subaerial parts of the confluent deltas—in part, probably, true fans—forming the Canterbury Plain (p. 203), and introduced the name "half-cone" for the majority of what are now termed "fans," because of their greater steepness.

steepest. The front or toe of the fan is roughly semicircular, but necessarily varies in outline according to any irregularities of the surface on which it is built, and also owing to interference of adjacent fans with one another.

Over a growing fan a stream flows in braided channels characteristic of an aggrading stream, and, taking new courses from time to time, flows by turns down every radius of the fan. In this manner the alluvium is distributed evenly, and the fan grows symmetrically. Any cross-profile of an alluvial fan, like a section of a cone, is convex, and this gives an explanation of the convex cross-profile of aggraded valleys previously referred to, for the floor of an aggraded valley is really a long narrow fan.

C. A. Cotton, photo.

Fig. 205.—Fan with a steep slope built by a small stream, near Cass, Canterbury, N.Z. This fan coalesces with another on the left.

Very steep fans are called *alluvial cones*, and there is a transition through these from alluvial fans to talus slopes.

Fans are generally abundant in mountainous regions where a normal cycle following ice erosion is still in its young stage; in the broad, aggraded valleys of Canterbury there is a fan at the mouth of every tributary stream (fig. 206).

A fan built by a vigorous tributary may extend completely across the main valley so as to dam the main stream and form a shallow lake, which overflows across the toe of the fan as a series of rapids. Taieri Lake, a small shallow lake in the Maniototo depression, in

Central Otago, seems to have been formed in this way through ponding of the Taieri River by the alluvial deposits of a vigorous tributary.

Without such actual ponding taking place the fan of a tributary may force the main stream against the valley-side, in which it may cut an embayment. Where the growth of fans is less vigorous, or the main stream more energetic, a swing of the main stream to the far side of its valley may allow of the development of a large fan, and a later swing in the other direction may cut a great part of it away. Cliffs will be cut along the front of the fan and the stream that built it will be forced to degrade again owing to the shortening

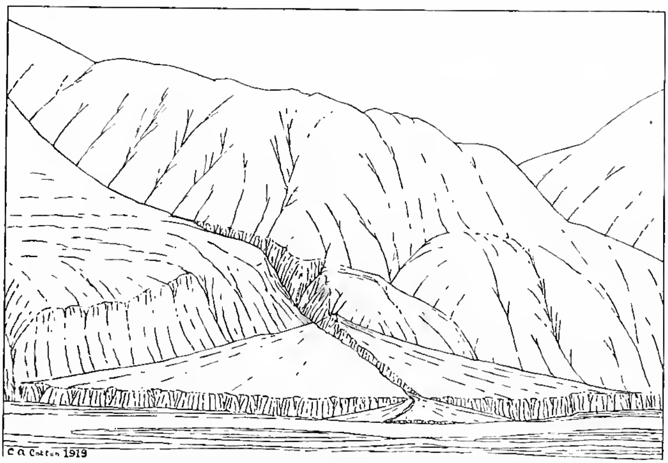


Fig. 206.—Truncated and partly reconstructed fan built by a tributary of the Rakaia River, Canterbury, N.Z., opposite Lake Coleridge Power-station.

of its course. It will entrench itself and become fixed in position along that radius of the fan it happened to be following at the time when the change from aggradation to degradation took place, as shown in figs. 204 and 206. Another swing of the main stream away from the mouth of the tributary will lead to the growth of a new fan in front of the remnant of the former one (fig. 206).

Much water sinks into the loose gravel of a fan, and in dry weather streams on the surfaces of fans may dwindle appreciably or even disappear altogether before reaching the margin. The underflow of ground-water may come to the surface as springs at

the margin of the fan. In some countries the water is obtained for irrigation of the lower slopes by driving tunnels horizontally into the alluvium.

On the stony surfaces of growing fans vegetation is scanty, for, as in the case of aggraded valley-floors, all parts are liable to flooding, and there is no certainty as to where the stream will next flow and deposit gravel. Where, however, the growth of the fan has ceased and the stream has become entrenched and fixed in position, the surface is no longer subject to flooding, and soil is formed by weathering of the superficial material, on which fresh gravel is no longer being spread.

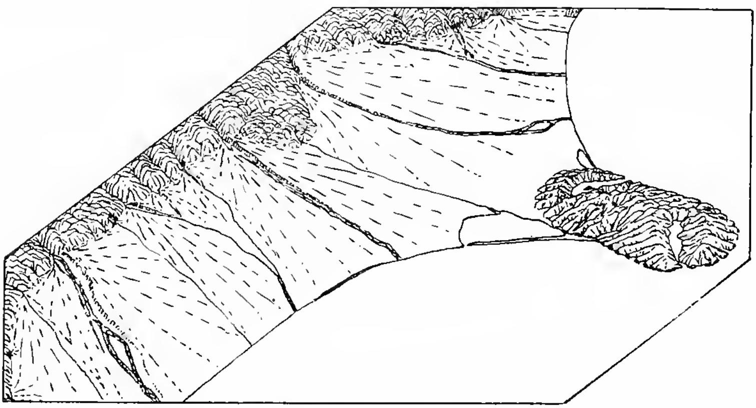


FIG. 207.—Diagram of the Canterbury Plain, N.Z., a piedmont alluvial plain.

In arid and semi-arid regions much fine waste as well as gravel is brought down by the intermittent torrents that build fans, and the whole of this may be deposited on the fans as the streams dwindle and disappear. The material of such fans, when irrigated, makes very fertile soils.

Piedmont Alluvial Plains.—Where a number of streams emerge from a mountainous area undergoing dissection on to a lowland, and build fans at their mouths, the fans if large are confluent, and thus form a continuous apron of waste along the mountain-foot. The nearly flat surface of such a waste-apron is termed a *piedmont alluvial plain.** It has an appreciable slope away from

* Or *bajada* (pronounced, and sometimes written, "*bahada*").

the mountains, and is made of up a number of convex areas each of which is one of the component fans.

The directions of the ever-changing courses of streams that are building fans or alluvial plains are, clearly, guided by the slopes of the alluvium they have themselves deposited. For these courses the name "autoconsequent" has been proposed by Speight (76, p. 97). Such courses become fixed if the habit of the stream changes from aggradation to degradation, as has occurred on the Canterbury Plain.

C. A. Cotton, photo.

FIG. 208.—A bay of Lake Tarawera, N.Z., completely filled by a delta that has been rapidly built of waste washed from the volcanic debris deposited during the eruption of 1886 (see Chapter XXIV).

The Canterbury Plain (fig. 207) may be described as a piedmont alluvial plain. (Strictly, it is made up of confluent deltas rather than fans, but the superficial parts of deltas and fans are alike.) The large rivers, Waimakariri, Rakaia, Ashburton, and Rangitata, by which the plain has been built follow radial courses on broadly convex areas (see fig. 207). Some smaller rivers, such as the Selywn, which have not themselves brought gravel from the mountains, follow consequent courses in the depressions between neighbouring convexities. The seaward slope of the Canterbury Plain varies from

40 ft. to 25 ft. per mile.* Other similar, though smaller, plains occur in various parts of New Zealand, bordering the sea.

The great plains in the centre of the North Island—*e.g.*, Kaingaroa and Waimarino Plains—though built of materials ejected from volcanoes are aggraded plains, the material having been carried and transported by running water. They may be regarded as confluent fans deposited by the numerous streams that cross them. The slopes of these plains are very gentle as compared with those that might be expected were the alluvial material ordinary gravel. Though somewhat coarse, however, the pebbles are extremely light, being mainly vesicular pumice. This alluvium can be carried by very sluggish streams, and may be transported long distances and ultimately deposited on very gentle slopes, as though it were fine silt.

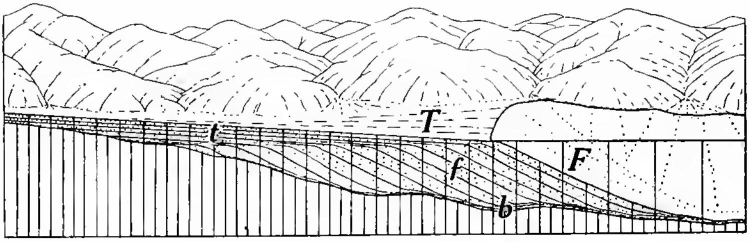


FIG 209—Diagram of the structure of a delta of coarse material at the head of a lake or bay.

Deltas.—Where waste is deposited at the mouth of a river in a body of standing water, either the ocean or a lake, the shoreline may be built forward, some new land being formed. Where such natural "reclamation" takes place the deposit at the rivermouth is termed a *delta* (figs 208, 209). A delta will be built only when more waste is supplied than can be disposed of by wave-action and tidal and other currents. Thus deltas are commoner in lakes than in the ocean, for in lakes there are no appreciable tides, and currents and wave-action are in general weaker than in the ocean. Deltas are frequently found also at the heads of sheltered bays (fig. 208). The name delta (from the Greek capital letter

* The origin of the Canterbury Plain by the growth of confluent "fans" was explained by Haast in 1864 (49).

delta, which is triangular) has been given because of the triangular shape assumed by the salients formed by deltas built out from straight coasts.

The small deltas built by steep-grade streams carrying coarse waste into lakes serve as a type of all deltas. Not only are the subaerially-formed surfaces of such deltas accessible for study, but also, very frequently, the parts laid down under water have been exposed owing to lowering of the level of the lake as the outlet has been cut down, and so the whole deltas have become land forms. The internal structure may often be seen also, where a

C. A. Cotton, photo.

FIG. 210.—Top-set and fore-set beds of a delta, head of Lake Wakatipu, N.Z. The fore-set beds are very regularly stratified. (Compare with fig. 209.)

delta-building stream has been compelled to degrade again and cut a trench across its delta owing to the lowering of the level of the lake, which is its local base-level (fig. 210).

The upper surface of one of these small deltas exactly resembles the surface of an alluvial fan, having been formed in the same way by an aggrading stream flowing in shifting channels, which was forced to add layer after layer of alluvium to the upper surface in order to maintain a sufficient slope as the width of the delta increased. This upper slope is termed the *top-set slope*

(*T*, fig. 209), and the alluvium of which it is built forms the *top-set beds* of the delta (*t*). The top-set slope extends a little below the lake-level, and is there replaced by a much steeper slope forming the front of the delta and termed the *fore-set slope* (*F*, fig. 209). The bulk of the gravel forming the delta and underlying the top-set beds is stratified in layers, termed *fore-set beds* (*f*), parallel with the fore-set slope. These entirely subaqueous beds dip at an angle of perhaps 20°, and the surface of each layer marks a former fore-set slope of the delta-front, the delta having grown forward as gravel and coarse sand were continuously poured over the edge and came to rest in the still, deep water at the angle of repose. The material is clean-washed, and is sorted according to size. Top-set and fore-set beds are clearly seen in a small delta projecting into Lake Wakatipu near Glenorchy, where, owing to lowering of the level of the lake, a trench has been cut through the delta by the stream that built it, exposing natural sections in its high banks (fig. 210).

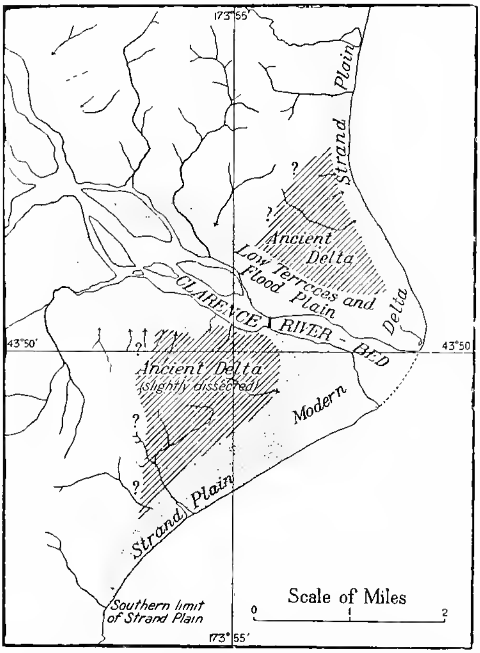


FIG. 211.—The ancient and modern deltas of the Clarence River, Marlborough, N.Z. The salient in the outline of the coast at the river-mouth is characteristic of typical deltas.

The mud that is brought into the lake does not accumulate with the gravel in the fore-set beds, but remains sufficiently long in suspension to be carried some distance. It finally sinks and forms thin layers of silt all over the bottom of the lake, smoothing over its irregularities and lying more or less horizontally. When a lake is

drained away by lowering of the outlet the silt deposit forms fertile plains. Some of the silt layers are covered over by the fore-set beds of the growing delta, and are there termed *bottom-set beds* (*b*, fig. 209).

Essentially similar deltas are built out into the sea by rivers with steep declivities bringing down large quantities of coarse waste—

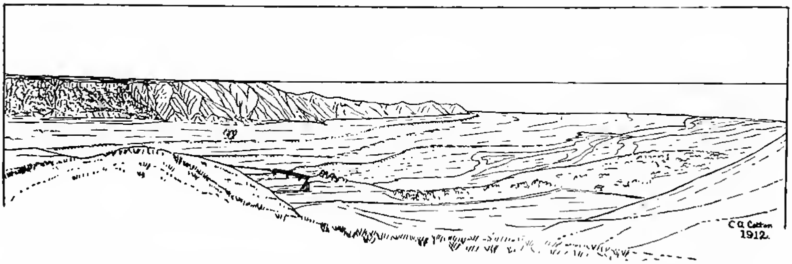


Fig. 212.—View of the uplifted and modern deltas of the Clarence River N.Z., from a point on the surface of the uplifted delta on the south side.

e.g., the Clarence River, Marlborough, N.Z. This river is now engaged in building a new delta in front of an earlier one (figs. 211–213), which has been partly destroyed by erosion owing to an uplift of about 600 ft. The uplift caused the main river to cut a broad

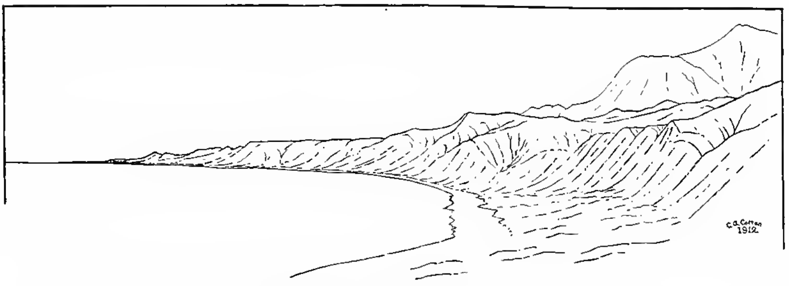


Fig. 213.—View of the Clarence delta from the north.

valley through its upraised delta, and also induced dissection of it by smaller streams. The ancient delta has also suffered partial destruction by marine erosion, which cut cliffs along the margin before it was protected by the growth of the new delta. The material of the fore-set portion of the ancient delta is principally

coarse gravel mixed with a little coarse sand, while the top-set beds consist of ordinary alluvium, in which layers of clay alternate with beds of coarse gravel. The fore-set portion is bluish-grey in colour, owing to its being deposited in water under deoxidizing conditions, and the top-set beds, which were deposited under subaerial conditions, are yellow to yellowish-brown.

Delta-plains.—The deltas built by large rivers of low gradient, carrying fine waste, are similar in a general way to those described above, but both the top-set and fore-set slopes are much less steep. The former may be almost quite horizontal and very liable to flooding. Near the margin accumulation of sediment may take place in

C. A. Cotton, photo.

FIG. 214.—The delta of the Waimea, at the head of Tasman Bay, N.Z.

lagoons enclosed by sand-bars thrown up by the waves along the sea-margin (seen in the distance in fig. 214). Swamps are thus formed, but, as the delta continues to grow, these areas may have their level raised by the accumulation of ordinary alluvium.

Such deltas form great plains (*delta-plains*) of rich land—the delta of the Nile, for example. In New Zealand delta-plains, many of them of coarse waste with a somewhat steep inclination (20 ft. or more per mile), are common. The Canterbury Plain has been already referred to as formed by the confluent deltas of a number of rivers. The Kaikoura Plain, in Marlborough, is similar, though on a much smaller scale, and connects the hilly Kaikoura Peninsula,

formerly an island, with the mainland in much the same way as Banks Peninusla is joined to the mainland by the Canterbury Plain. A considerable area of the lowland of western Wellington is formed by the delta of the Manawatu. The Southland Plain, the Heretaunga Plain (in Hawke's Bay), the Wairau Plain (with a very gentle slope, and built of fine silt), the Waimea Plain (at the head of Tasman Bay, fig. 214), and a number of others are delta-plains partly filling bays.

Instability of River-courses on Deltas and Aggraded Plains.— The great plains bordering the Hoang-Ho in China, which support a population of many millions, have been built by aggradation. They form a delta with an area of about 100,000 square miles. The river frequently changes its course, and there have been many disastrous floods. The Hoang-Ho has discharged sometimes on the northern and sometimes on the southern side of the mountainous peninsula of Shan-Tung, formerly an island, which has been joined to the mainland by the growth of the delta. The material of which the plains are built is a fine yellow silt.

Another illustration of the instability of river-courses on deltas is afforded by the delta of the Colorado River, in western North America. This delta extended completely across the Gulf of California, with the result that the head of the gulf first became a lake and then became almost completely dried up, the climate being arid. A plain, the Imperial Valley, was thus formed far below the sea-level, with a small salt lake, the Salton Sink, at the lowest point. No doubt the river, if left to itself, would at some future time have temporarily taken a course down the northern side of its delta and filled the lake-basin up again. It has been refilled thus many times in the past, drying up more or less completely each time the Colorado took a more direct course to the sea. This time, however, man hastened the process by attempting to lead a small stream of water from the river into the Imperial Valley for irrigation purposes. The river enlarged the irrigation canal, and, abandoning its former course for the new one, poured its whole volume into the valley. At enormous expense the Colorado was again turned into its former channel, but not until a great part of the Imperial Valley had been converted into a large lake, the Salton Sea, which is now shrinking again as the water evaporates.

It is clear that the rivers building the New Zealand deltas mentioned above must have had constantly changing courses in order to spread their waste evenly over the surfaces. Some of the more recently abandoned courses can easily be traced. The delta of the Waimakariri, for example, is still growing, and several former channels of the river—wastes of bare gravel, with occasional sand-dunes—are traceable in the vicinity of Christchurch (fig. 215).* Apparently the Waimakariri discharged south of Banks Peninsula at a not very distant period. Similarly the deltas forming the Kaikoura Plain are still growing, and the Kowhai River is known to have changed its course in modern times from the north to the south side of Kaikoura Peninsula.

Great changes in river-courses take place inland also where aggradation is in progress. Striking peculiarities in the courses of

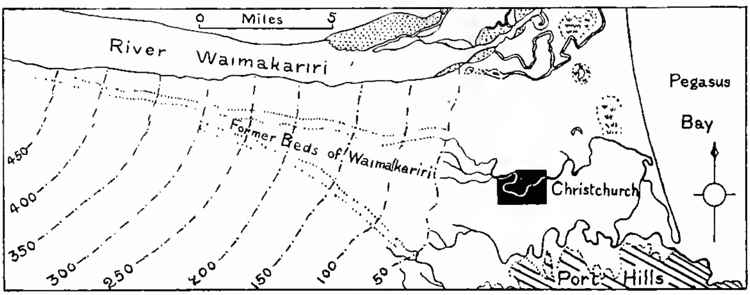


Fig. 215.—Abandoned channels of the Waimakariri River. After Doyne (with interpolated contour-lines, at 50 ft. intervals, on the plain).

some of the rivers of Southland may be thus explained. Alluvial filling of a valley or depression through which a river flows may result in spilling-over of the stream of water and waste at some gap in the rim of hills surrounding the depression. The new course of the stream will, in general, be too steep, and when this is the case degradation will take place in it and will work up-stream from the point where spilling-over took place. The river will thus become fixed, at least for a time, in the spill-over course. Such a river is sometimes described as "diverted by alluviation" (8, p. 142).

The diversion, on the other hand, may not be permanent. The new valley and the trench excavated in the aggraded valley up-

* W. T. Doyne, 40.

stream may become filled up eventually, if the supply of waste keeps up; and when the new course is built higher by aggradation than the original course the stream will spill back again, and it will continue after that to occupy and aggrade the two courses alternately. The Oreti River, in Southland, flows south-eastward across a broad alluvium-filled depression known as the Five Rivers Plain, but, instead of following the even slope of the aggraded surface across the Waimea Plain farther to the south-east (fig. 216), turns southward through a relatively narrow gap in the north-western end of the Hokonui Hills. The river-valley through this gap is aggraded, and the gradient of the course now followed by the river, as given by railway data, is the same as that of what was obviously a former course across the Waimea Plain. It wou'd seem that the great depression of the Five

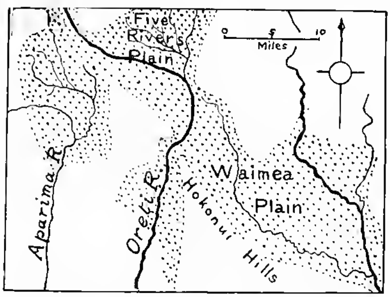


FIG. 216.—The course of the Oreti River, Southland, N.Z.

Rivers and Waimea Plains was filled with alluvium by the stream which occupied it until the alluvium spilled over a low col in the already maturely dissected Hokonui Hills,* and that the river, wandering freely on the aggraded plains, has since followed sometimes the one outlet and sometimes the other, keeping both courses built up to the same gradient. The Oreti has another alternative course down the valley of the Aparima.

The Structure of Alluvial Deposits.—Alluvial deposits, whether in fans or the top-set beds of deltas or underlying aggraded plains, exhibit a rough stratification parallel to the surface (fig. 217). As might be expected from their mode of accumulation, the beds are irregular, thickening and thinning rapidly, and grading laterally into

* This explanation was first suggested to the author by Professor W. M. Davis.

material that is either coarser or finer. On account of its irregularity the arrangement of the material is termed *lens and pocket* stratification. There is nothing like the complete sorting that takes place during deposition in the sea or a lake, where the waste of different grades of fineness is deposited in different places, so that the deposit in a particular portion of any stratum is of even size. There is, however, in alluvial deposits an incomplete sorting according to size,

L. Cockayne, photo.

FIG. 217.—Bedded alluvial gravel of a piedmont alluvial plain (the Canterbury Plain, N.Z.), exposed in the high bank of the Waimakariri River, which has here cut a channel of considerable depth below the surface of the plain.

lenses of clay being deposited in abandoned channels and afterwards covered with perhaps coarse gravel. Coarser and finer gravel beds may be present also, but there is generally a mixture of coarse and fine gravel with still finer material. In fans built by vigorous mountain-streams large boulders occur scattered through the gravel.

CHAPTER XVI.

COMPLICATIONS IN THE NORMAL CYCLE DUE TO THE OCCURRENCE OF REGIONAL MOVEMENTS.

Accidents and interruptions. Various kinds of interruptions. Movements of the land and of sea-level. The new cycle. Gradation following interruption. Interruption by regional depression. Aggradation not a proof of subsidence. Interruption by regional uplift (emergence).

Accidents and Interruptions.—The course of the normal cycle may be cut short at any stage by one of several kinds of *accidents* and *interruptions*, as they have been termed by Davis. Accidents are of two kinds, *climatic* and *volcanic*. The climatic accidents which produce the most important effects are *refrigeration*, which introduces glacial erosion, and a *change to aridity*, which introduces the work of wind as a dominant or at least as a very important factor. By the phrase " volcanic accident " is meant the outbreak of volcanic activity, which, occurring at any stage of a cycle, will very rapidly alter the aspect of the topography, building up, perhaps, an entirely new surface upon which erosion must begin its work afresh. The work of wind, glacial erosion, and volcanic activity will be taken up in later chapters.

Various Kinds of Interruptions.—Interruptions of the cycle, which may be now discussed, are due, as a rule, to earth - movements, though sometimes also to fluctuations of sea-level. Small changes in the relative levels of land and sea, whether due to movements of the land or fluctuations of sea-level, are, in the long-run, negligible if they are oscillations about a mean position. When, on the other hand, they are cumulative in one direction, the result is that the former base-level is replaced by a new one either higher or lower in the land-mass. It may be assumed that the land, after such movement has taken place, again stands still. The former cycle of erosion is cut short as a result of the change in the position of base-level, and a new cycle is inaugurated.

In addition to simple regional movements of uplift and subsidence of the land relatively to sea-level (*emergence* and *submergence*), movements involving deformation, dislocation, and tilting of the former land-surface in the area studied are also of great importance.

Movements of the Land and of Sea-level.—The interrupting effects of regional movements—of movements, that is to say, sensibly uniform throughout the area studied—are indistinguishable by their results from those of rise or fall of sea-level due to fluctuation in the volume of the ocean waters, or to some change in the capacity of the ocean-basins produced by deformation in some remote part of the world. It is sometimes convenient, therefore, to describe such events as "submergence," or "positive movement of the strand," and "emergence," or "negative movement of the strand." Actual rise and fall of the ocean-surface must be regarded as a probable cause of some movements of the strand-line (and such probable movements are sometimes distinguished as "eustatic"); but it is fantastic to assume, as has sometimes been done, that all submergences and emergences are due to that cause.

It is often evident from comparison with a neighbouring area that in a particular district the submergence or emergence that has taken place has been chiefly or wholly due to actual sinking or rising of the land. Thus, in the northern part of the South Island of New Zealand, in the Marlborough Sounds district (p. 217), the latest movement was clearly one of subsidence, while in eastern Marlborough, which is separated from the above-mentioned district only by the delta of the Wairau River, the evidence as clearly points to very recent uplift (p. 223).

Even within a district showing evidence of emergence or of submergence throughout, the amount of this may vary from place to place, indicating tilting or other uneven movement of the land, and thus showing that movement of the land has been responsible for some—and, the presumption is, the whole or greater part—of the emergence or submergence.

The New Cycle.—In a general way the stages of a cycle introduced by a movement or movements interrupting the cycle previously current are the same as the stages of a first cycle, and when fully mature and senile the relief is such as has already been described for those stages. Though of the same general type, the

topographies of successive cycles may differ considerably in details, however. Adjustment to structure, for example, will not generally be completed in a single cycle, but will continue in those stages of succeeding cycles in which the streams are vigorously eroding.

The younger stages of the new cycle initiated by interrupting movements demand special attention, for the land-forms developed in them are seen side by side with those of the interrupted cycle, and are closely related to them. This phase—replacement of the topography developed in one cycle of erosion by that developed in the cycle which follows—is characterized by special forms governed by the nature of the interrupting movements.

F. G. Radcliffe, photo.

FIG. 218.—Kenepuru Sound, an arm of Pelorus Sound, a drowned valley-system.

Gradation following Interruption. — In all cases after an interrupting movement the grading processes, degradation and aggradation, come into operation, grading both streams and surfaces with respect to the new position of base-level. After the movement has taken place, parts of the beds of formerly graded streams are, for example, too steep under the new conditions. The velocity of such streams is accelerated, and they have energy to spare beyond that required to transport their loads of waste. The streams degrade their channels, therefore, reducing their steepness until the graded

F. G. Radcliffe, photo

Fig. 219.—Delta of the Pelorus River, at the head of Pelorus Sound. N.Z.

G. L. Adkin, photo.

Fig. 220.—Braided course of the Ohau River, western Wellington, N.Z., showing the convexity of its bed.

condition is again established. If, on the other hand, part of the course of a river has become too nearly level, the stream becomes too sluggish to carry its whole load, and therefore deposits part of it in its channel, thus building up and steepening it until again graded.

Interruption by Regional Depression.—When a cycle of erosion is interrupted by an even, general subsidence of the land, or by a rise of sea-level, the lower part of each river-valley is at first invaded by the sea. It becomes a *drowned valley*, and forms an estuary or harbour, like Pelorus Sound (fig. 218) and many other deep indentations of the New Zealand coasts (see Chapter XXVIII), which are the results of drowning due to even, or nearly even, submergence. As the new cycle thus inaugurated progresses, the streams, both large and small, build out deltas in the still water at the heads of the bays or estuaries into which they now flow (fig. 219); and all the streams thus grow in length again seaward. As delta-building streams, if previously graded, must aggrade (as shown in fig. 209) in order to continue flowing and maintain grade, it follows that valleys in a region where subsidence has taken place become more or less deeply aggraded.

Aggradation not a Proof of Subsidence.—Aggradation in previously graded valleys may be brought about in more ways than one, and does not in itself afford definite proof of subsidence. Aggradation is caused by any increase in the load of waste or decrease in the amount of water in a graded stream, the load in the latter case remaining constant; for either of those changes results in overloading, and the result of overloading is deposition of the excess load until grade is re-established. A disturbance of the balance between volume and load may occur as a result of stream-capture, or it may be a result of a small climatic change. Desiccation of climate (change to drier conditions) both decreases river-volumes and, by reducing the protection afforded to the soil by vegetation, increases the supply of waste. Thus aggradation may follow a minor climatic accident of this kind, while degradation may follow a change towards moister conditions. Increased rainfall generally increases the ratio of volume to load, as it augments stream-volumes, and may also reduce the supply of waste by encouraging the growth of vegetation, a condition which leads to downward corrasion until grade is re-established.

Many New Zealand rivers are now building up the floors of valleys previously excavated, either in solid rock, as in the case of the rivers of eastern Marlborough, or in alluvium, as in the case of the large rivers of Canterbury, which, after cutting deep trenches in the gravel of the Canterbury Plain, are now proceeding to fill these up again, as shown by their braided courses on convex valley-bottoms (73, p. 27). This change to aggradation seems to have taken place very recently, and it is perhaps a result of a climatic oscillation towards aridity. A factor operating in the same direction, which will account for a part of the aggradation, is the disturbance

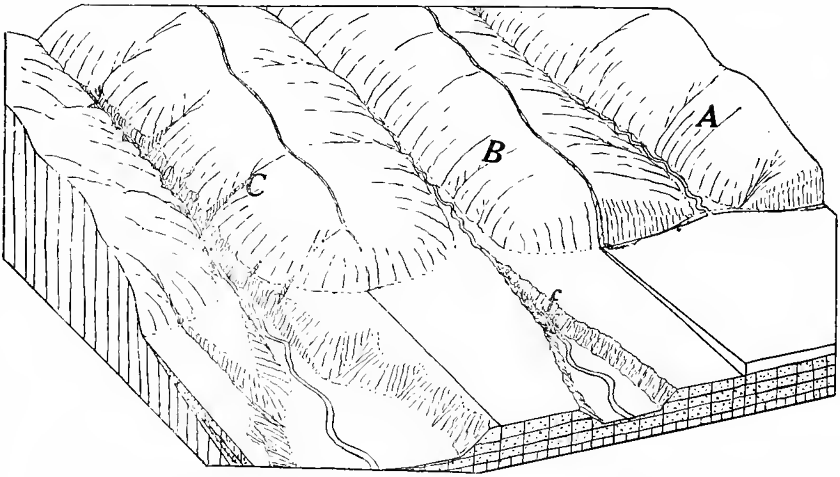


FIG. 221.—Diagram illustrating interruption of the cycle by regional uplift. *A*, before uplift; *B*, rapids developed at the fall-line; *C*, valley-in-valley forms developed in the old land.

of the natural vegetation due to the introduction of sheep, rabbits, and other animals, and also to grass-fires, which results in rapid erosion (fig. 197) and overloading of streams. Similar results follow the clearing of forests (fig. 196). Aggradation now in progress in the streams of western Wellington (fig. 220) may be connected with an advance of the shore-line seaward (see Chapter XXIX).

Interruption by Regional Uplift (Emergence).—After a regional uplift (or emergence due to lowering of sea-level) the relief at the end of the cycle that is interrupted by this event (young, mature, or old, as it happens to be) is the initial relief of a new

J. A. Thomson, photo.

FIG. 222.—Valley-in-valley form in the valley of the Awatere, a revived river.

C. A. Cotton, photo.

FIG. 223.—Valley-in-valley form in the valley of the Shotover River, Otago, N.Z.

cycle. There are no immediate changes in this surface as a result of such uplift; but the base-level has been lowered and changes follow in due course. There is a new shore-line, and between this and the former shore-line, bounding the former land area (fig. 221, block *A*), a strip of sea-floor has been uplifted to become land, a coastal plain (p. 69), of which only the part nearest the old land is shown in fig. 221. The rivers of the old land, with the redissection of which we are now concerned, are extended across the coastal plain, and in their lower, extended courses their gradients are in general steeper than is necessary for the transportation of their loads (Chapter VI). Trenches across the coastal plain are soon cut, therefore, with their heads near the former shore-line, where the streams have cut down to the hard rocks of the old land and there are rapids or falls (fig. 221, block *B*, *f*). For this reason the former shore-line—or, rather, the line at which streams cut down to the floor of older rocks underlying the weak sediments of the coastal plain—is sometimes termed the *fall-line.* The streams are not now graded throughout their length, their profiles being too steep at the fall-line. Each stream in the oversteep part of its course has sufficient velocity and energy to degrade, and so the rapids work up-stream, the river down-stream from them becoming graded with respect to the lowered base-level. This headward erosion with the development of a new valley within the former valley (fig. 221, block *C*) goes on rapidly because of the abundance of water, for the streams drain valley-systems developed in the preceding cycle. As the head of the newly cut inner valley advances up-stream, the cross-profile of the valley becomes that of a steep-sided young valley below and of a more widely opened valley of the preceding cycle above. This condition is sometimes termed *valley-in-valley,* and the river is said to be *revived.* Between the slope of the valley-side or valley-floor of the former cycle and that of the valley-side of the new cycle there is a sharp angle, or *shoulder* (figs. 222, 223).

There is no tendency to deepen the valley of the earlier cycle except by headward erosion of the inner valley, and above the rapids or falls marking the head of this the older valley retains its form, undergoing only such slow modification as would have been in progress had an interrupting movement not taken place. This is expressed by saying that the earlier cycle is still *current* until the features developed in it are encroached upon by those developed in the succeeding cycle.

CHAPTER XVII.

COMPOSITE TOPOGRAPHY AND RIVER TERRACES.

Rejuvenation and composite topography. Entrenched meanders. Terraces developed in connection with entrenched meanders. Valley-plain terraces. Terraces of rock and of alluvium. Terraces developed during continuous valley-excavation. Flights of terraces of composite origin. The slopes of river terraces.

Rejuvenation and Composite Topography.—After a regional uplift the earlier topography is destroyed only a little at a time by the encroachment of the features developed in the new cycle, and when the surface as a whole is considered it is clear that the former cycle is current until the surface developed in it is encroached upon by the young trenches of tributary streams compelled to degrade by the deepening of their mains, and also by the young slopes of the new cycle similarly degraded (figs. 224, 225).

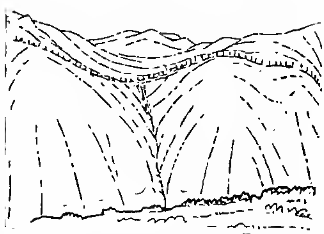


FIG. 224.—Young, steep slopes of a new cycle encroaching on a mature surface (above), in a truncated valley overhanging the Ngahauranga Gorge, Wellington, N.Z.

The presence of topographic features developed in several cycles may demonstrate a succession of uplifts. In other cases a succession of uplifts may have taken place, but the cycle introduced by the latest of them may be so far advanced that all traces of the forms developed in earlier cycles have disappeared. Some parts of the land-surface have been above the sea and subject to subaerial erosion for enormous periods and have been uplifted from time to time, so that, in the aggregate, a vast thickness of rock has been removed by erosion.

The gradual replacement of forms of one cycle by forms of the next is called *rejuvenation;* and while the relief comprises forms

developed in two (or more) cycles the topography is said to be *composite.* The "surface has been developed partly in relation to one base-level and partly in relation to another" (Davis).

Examples of composite topography are very common in New Zealand, where movements, often of uplift, have been recently in

C. A. Cotton, photo.

FIG. 225.—Composite topography—mature forms above, and young valley-side slopes of a newer cycle below, Kaiwarra Gorge, Wellington, N.Z.

progress, not continuously, however, but separated by relatively long periods of still-stand during which surfaces have been developed to a more or less mature stage. Among many areas characterized by rejuvenation the neighbourhood of Wellington may be noted,

where features developed in two cycles may be very clearly distinguished, especially in the Makara, Kaiwarra, and Porirua valley-systems. In the Makara Valley (fig. 226) benches which are now from 100 ft. to 200 ft. above the level of the stream are remnants of a broad floor of a former mature valley. The hill-slopes on the valley-sides are still very generally accordant with this floor. Within this older valley is the valley of the present cycle, in which the stream now flows. In places its floor opens out as a broad flood-plain. Young trenches extend up the valleys of small tributaries (though not, as a rule, to the heads of them), their steep sides articulating by a shoulder with the more mature

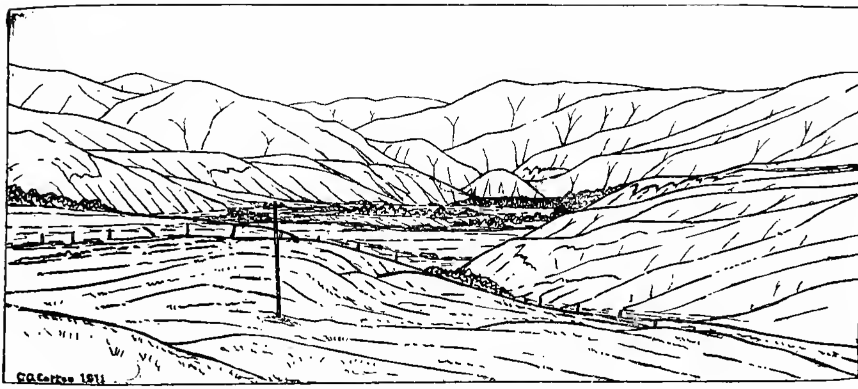


Fig. 226.—Composite topography in the Makara Valley, Wellington, N.Z.

slopes of the former cycle above. Similar forms in the Porirua Valley may be seen from the railway, which enters the head of the valley at Johnsonville upon the valley-floor of the earlier cycle, follows a bench of this for a short distance, and then descends, farther down-stream, to the flat floor of the inner and younger valley.

In eastern Marlborough very young valley-in-valley forms occur, indicating that quite a short time has elapsed since uplift initiated rejuvenation. The lower course of the Awatere River, for example, flows in a young trench incised about 100 ft. below the surface of its former flood-plain, which has, in the weak rocks of the lower valley, a width of several miles. (Fig. 222 shows the rejuvena-

tion farther up the valley.) Small tributaries of the Awatere are revived only close to their junctions with the main river, and descend by series of falls and rapids from the level of the uplifted valley-plain of the Awatere to the present level of the river in a few hundred yards. Similar features are found in the valley of the Kekerangu, farther south, which also crosses weak rocks in its lower course, and there flows in a narrow inner valley flanked by a wide bench of an uplifted valley-floor (fig. 227). A plaued surface of a still earlier cycle, which has been submaturely dissected, and is indicated by the even sky-line of the hills southeastward of the lower Awatere Valley, has already been referred to (p. 130 and fig. 133).

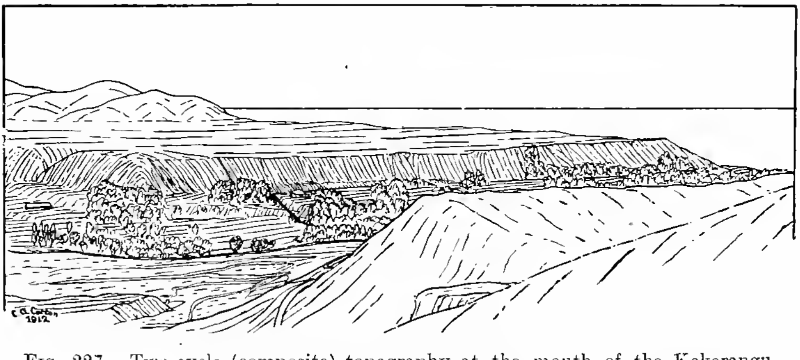


FIG. 227.—Two-cycle (composite) topography at the mouth of the Kekerangu River, Marlborough, N.Z.

Two-cycle topography in the Clarence Valley, Marlborough, is shown also in fig. 121 (foreground and middle distance).

Throughout the North Auckland Peninsula and in the neighbourhood of the city of Auckland (fig. 130) composite topography is well marked, broad planed areas now far above base-level indicating advanced maturity of valleys in a former cycle or cycles, while narrow valleys dissecting these plateaux and benches point to a less advanced stage of dissection after uplift. The valleys of the latest period of degradation are now in many cases occupied by arms of the sea, which shows that uplift was followed by subsidence, though the depth of subsidence did not equal the height of the previous uplift.

Entrenched Meanders. — When flat-floored valleys in which rivers follow meandering courses (fig. 228, block *A*) are present in a region that is uplifted so that valley-in-valley forms are developed, the newly deepened inner valleys are guided by the windings of the river-channels (block *B*). The windings of the inner valleys upon the flat floors (now dissected valley-plains) of the older valleys are termed *entrenched meanders* (fig. 229).

Free swinging of meanders on the flood-plain must, obviously, be checked at once when the stream begins to cut downward; but there is still the same tendency as before to cut into the concave bank, against which the strongest current impinges. Thus as the meandering channel is deepened, if the stream is a vigorous one, the curves are enlarged and each is pushed a short distance down the valley, just as in the first development of stream-curvature. As a result the slopes descending from the ends of spurs of the abandoned flood-plain, and from their down-stream sides, to the stream below are slip-off slopes and are less steep than the undercut slopes descending to the stream along its concave banks (see fig. 228, *B*).

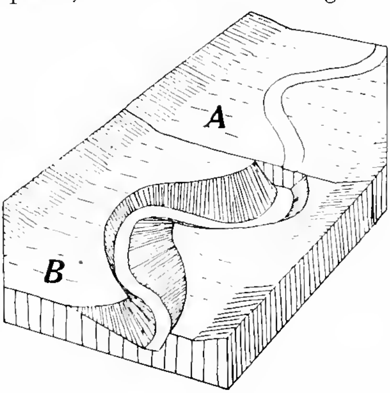
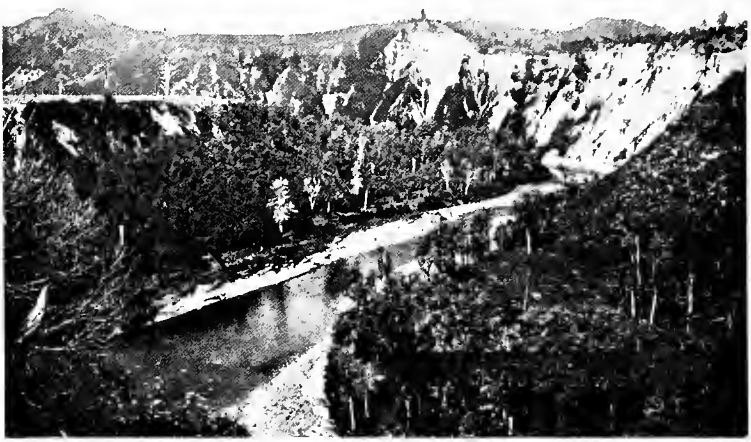


FIG. 228.—Entrenched meanders.

Terraces developed in connection with Entrenchment of Meanders. — Sometimes the more gently sloping convex side of the inner valley of an entrenched meander descends as a series of terraces, which seem to mark a series of pauses during discontinuous uplift. During each pause the river, if eroding weak rock and more or less keeping pace in its down-cutting with the uplift, swings laterally and cuts a narrow flood-plain, only to go on deepening its valley again, and to repeat this process after each small movement of uplift. The resulting valley form is illustrated in fig. 230, which represents a portion of the valley of the River Awatere, Marlborough, N.Z. It will be noted that the lines traced by the terrace-fronts are convex, and also that

occasionally two terrace-fronts merge into one, where a part of one terrace has been cut away during the development of the next lower temporary floor. Some of the temporary floors may thus have been entirely destroyed. Fig. 231 shows a flight of similar terraces in the valley of the Waipara River, Canterbury, N.Z.

Valley-plain Terraces.—In areas of valley-in-valley or composite topography—such, for example, as the Awatere Valley (p. 223)—valley-plains of the earlier cycles, or remnants of them, form well-marked terraces. They record the occurrence of periods of still-stand of much longer duration than those previously referred to—of



F. G. Radcliffe, photo.

FIG. 229.—Entrenched meanders of the Rangitikei River, near Mangaweka, N.Z.

sufficient duration to rank as cycles; and it is generally possible to correlate one remnant with others in the same or even in adjacent valleys, and so to reconstruct in imagination the surface of which it once formed a part. Fig. 227 shows a broad terrace of this kind bordering the Kekerangu River near its mouth.

Such terraces are common in New Zealand valleys. Near Seddon, for example, broad terrace plains border the Awatere River on each side. Their combined width is about three miles, and their height above the present river-bed about 120 ft. In addition, terrace remnants hundreds of feet higher are numerous on the

valley-sides, bearing witness to the occurrence of more than one cycle of erosion. Similar terraces occur in the Clutha Valley (fig. 232) and in the valleys of the Rangitikei (fig. 229) and neighbouring rivers of the North Island, and in the rivers of eastern Wellington. Such terrace plains and remnants were recognized in New Zealand by Hochstetter in 1859. They are found principally in areas of soft rocks, upon which rivers attained an advanced stage of maturity in each cycle of erosion, though generally this was by no means the case in adjoining areas of resistant rocks. In some

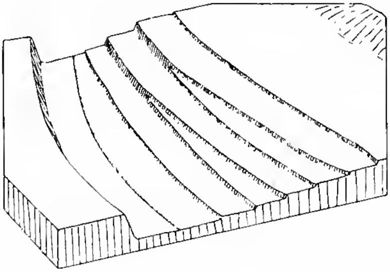


Fig. 230.—Diagram of terraces on the slip-off slope of an entrenched meander of the Awatere River, N.Z.

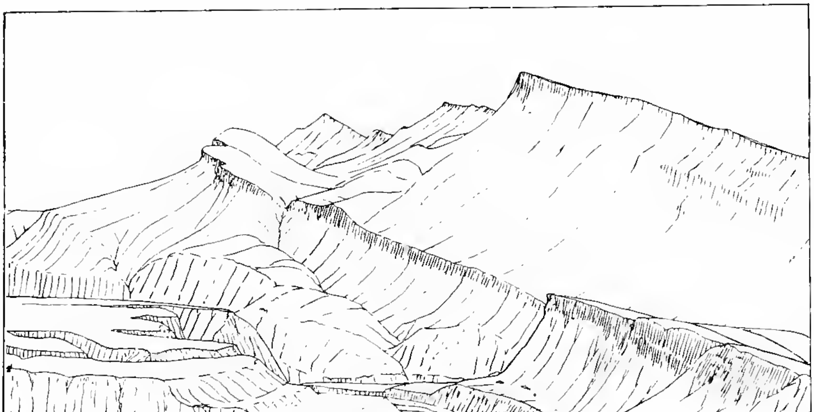


Fig. 231.—Part of the Waipara Valley, Canterbury, N.Z., showing, in the centre, a flight of terraces.

districts, however, vigorous rivers cut valley-floors sufficiently wide to form terraces even in the more resistant rocks (fig. 233).

C. A. Cotton, photo.

Fig. 232.—Valley-plain terraces bordering the Clutha River, near Clyde, N.Z.

Tourist Department, photo.

Fig. 233.—Flight of terraces in the Waiau Gorge, North Canterbury, N.Z.

Terraces of Rock and of Alluvium.—Terraces are often formed of solid rock with a thin veneer of gravel on the top—the gravel of the former valley-floor. Such terraces are illustrated in fig. 234, B, developed from the valley-plain A (see also fig. 235). When, however, terraces are remnants of aggraded valley-plains (fig. 234, C) they may be composed of gravel throughout (D), or of solid rock below and a thick mass of gravel above (E).

The majority of the terraces shown in the foregoing figures are composed of rock; but gravel terraces are common in New

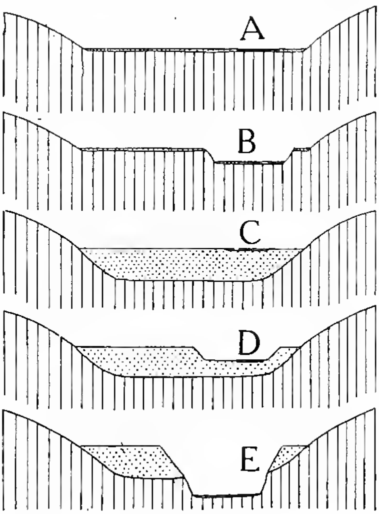


FIG. 234.—Terraces of solid rock and of alluvium.

Zealand also, probably attaining their greatest development on the sides of the valleys which trench the Canterbury Plain.

Terraces of a peculiar kind are to be seen in some valleys in Otago, which, after being aggraded, were widened by lateral corrasion in such a way that, when later the streams in them began to cut downward again, they were flowing in some places on solid rock to one side of the filled valleys. Such portions of valleys are now bordered by terraces presenting a front of solid rock to the river; but the solid rock is only a narrow bar between the present trench and the filled valley, and the terrace is underlain some distance back by a great depth of alluvium. This state of affairs

has been revealed in some cases by mining operations, the gold-bearing alluvial filling of the aggraded valleys having been in part removed by sluicing. This is the case in the Shotover Valley, which is represented in the block diagram, fig. 236, and sketch, fig. 237. Deep gravel underlies the terraces which appear to the right in fig. 237 and on the distant bank of the river in fig. 236; and between the aggraded valley and the narrow trench now occupied by the river is a barrier of schist rock. At one point the rock barrier has been pierced by a tunnel to carry away the tailings from a sluicing claim.

C. A. Cotton, photo.

FIG. 235.—Rock terrace in the valley of the Wairoa River, Nelson, N.Z.

Terraces developed during Continuous Valley-excavation.—A degrading river may be constrained to deepen its channel very slowly, perhaps owing to very slow uplift, but more frequently owing to the fact that it crosses a barrier of hard rock. Up-stream from the barrier the river may flow over weak material across which it maintains with ease a graded condition while the hard-rock ledge—a local base-level—is gradually lowered. Such conditions exist where transverse rivers cross outcrops of alternating weak and resistant strata. They occur also in somewhat winding valleys

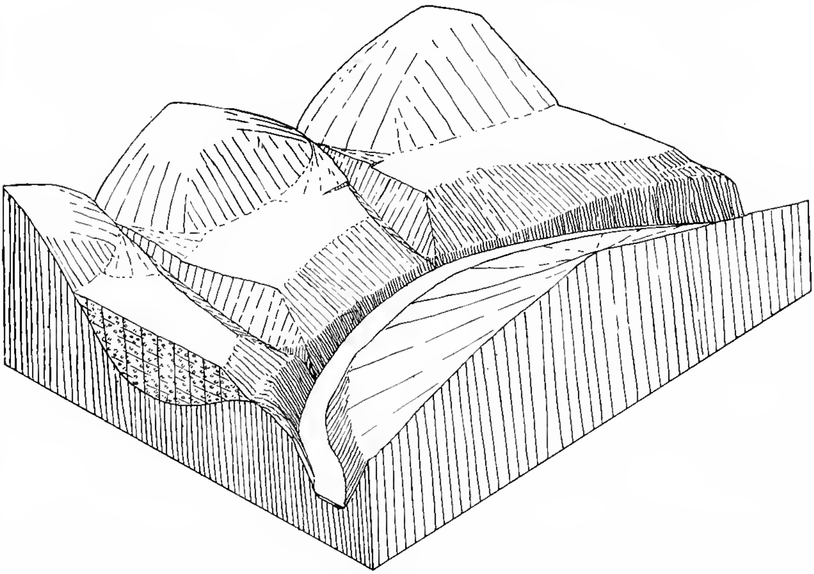


Fig 236.—Block diagram of a portion of the valley of the Shotover River, N.Z.

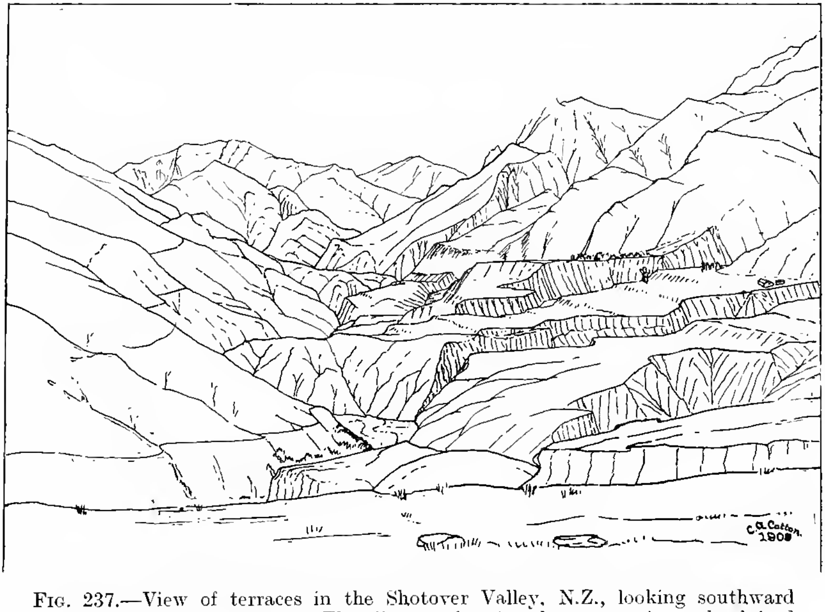


Fig. 237.—View of terraces in the Shotover Valley, N.Z., looking southward down the valley. The alluvium forming the terraces is partly sluiced away. The river-banks are solid schist rock.

which have been filled either with alluvium or with glacial drift. A river re-excavating a valley of this kind and taking a course across a buried spur has its down-cutting so retarded thereby that it develops a graded, fully mature, and broadly opened valley farther up-stream. Such a river, in its graded reaches, continues during down-cutting to follow a meandering course over a flood-plain; the meanders migrate down-stream, and the meander belt swings from side to side of the valley-floor. Since, however, the stream is degrading, each time the meander belt approaches the valley-side its floor is at a lower level than that of the previous time. If it quite reaches the valley-side it completely cuts away the former flood-plain, but if not it leaves a remnant as a terrace. Fig. 238 illustrates this method of terrace-formation. Block *A* represents the river flowing on a broad valley-plain in an alluvium-filled valley. In block *B* degradation has begun, and a strip of the width of the meander belt has been incised to some depth, leaving a terrace of the same height on each side of the valley. In block *C* the meander belt, now more deeply incised, has swung towards the right, leaving as a second terrace a portion of what was its floor in block *B*. Block *D* represents a later stage, in which a third terrace has been left. It will be noted that the fronts of terraces developed in this way are concave, as they mark the farthest sideward migration of a convex curve of the meander belt.

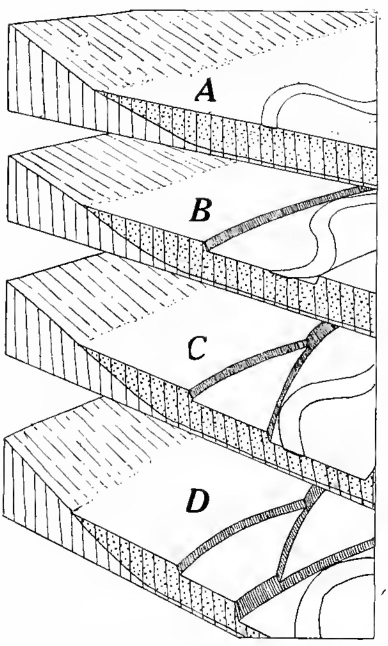


FIG. 238.—Diagram to explain the development of terraces by a river degrading slowly in soft material.

Such terraces as these are not commonly found in the valleys of rivers that are degrading in homogeneous material, even though the material be soft, for in this case there is nothing to check the lateral swinging of the meander belt at the lower levels, and so the higher floors are liable to be entirely cut away. When, however, there are bars of solid rock such as are provided by buried

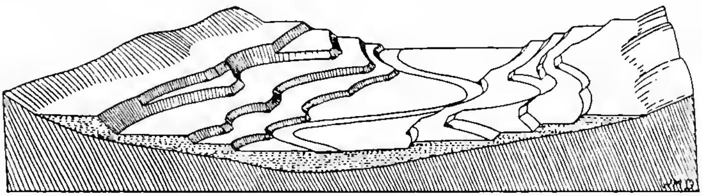


FIG. 239.—Diagram of terraces of soft material protected by rock ledges formed by buried spurs, the rocks of which are shown outcropping on each terrace cusp. (After Davis.)

spurs in the soft alluvium of a filled valley, these, when they become exposed, prevent further swinging and so protect series of terraces both up-stream and down-stream from the rock ledges (4, pp. 514–86). Upon the ledges the concave fronts of up-stream and down-stream portions of terraces meet in cusps (fig. 239).

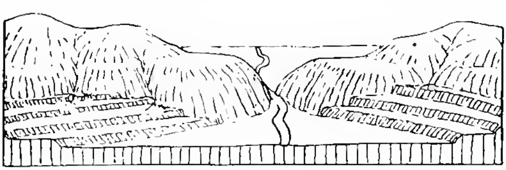


FIG. 240.—Diagram of terraces protected by a hard-rock barrier through which the river has cut a gorge.

When rock barriers occur, through which the rivers cut gorges, these also protect terraces (4, p. 557 ; 73, p. 24). As the streams are constricted in gorges at the barriers (fig. 240), these form fixed nodes at which swinging of the stream is prevented, but both up-stream and down-stream from the barriers, the influence of which extends but a short distance, the streams swing freely from side to

side as they cut downward through the relatively soft material. Close to the gorges, therefore, especially on the down-stream side, terraces survive which are remnants of flood-plains completely cut away in other parts of the valleys.

Fans of tributary streams or cones of talus from the valley-side may maintain their position, if the supply of waste to them keeps

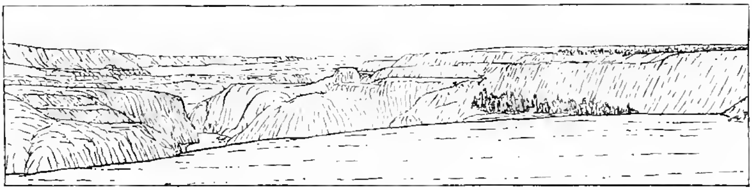


Fig. 241.—Terraces at Rakaia Gorge, N.Z. (After a photograph by R. Speight.)

up, while degradation is going on in the main valley. By forcing the main stream towards the opposite side of the valley they prevent its wide swinging and form fixed nodes similar to those formed by gorges; or, at least, they prevent swinging towards the side on which they occur. Thus they protect flights of terraces, especially on the down-stream side (73, p. 25).

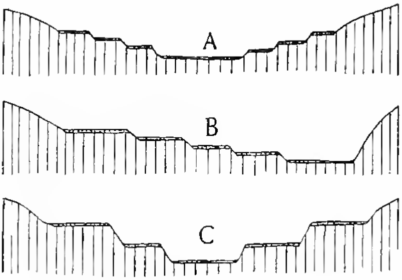
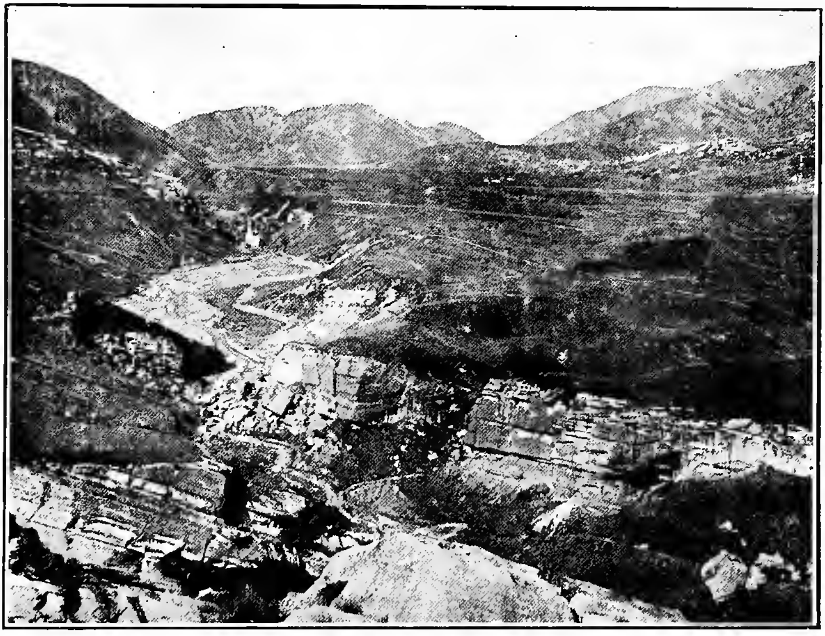


Fig. 242.—Diagrams of terrace profiles.

Beautiful examples of rock-defended terraces occur in the valley of the Rakaia River, at the Rakaia Gorge (fig. 241). The terraces are composed of alluvial gravel, through which the river has cut slowly downward, and the defending ledges are supplied partly by a buried ridge of volcanic rock and partly by buried glacial

moraine. Below the level of the principal terraces the river has cut a deep gorge through the barrier of volcanic rocks.

Terraces formed during continuous valley-excavation will not occur at the same height on opposite sides of a valley, but if present on both sides will alternate as in fig. 242, A; for, obviously, the meander belt takes a considerable time to migrate from one side of the valley to the other, and by the time it has crossed it has reached a lower level. Neither is there necessarily a symmetrical develop-



R. Speight, photo.

FIG. 243.—Flight of terraces in the Broken River Basin, N.Z.

ment of terraces on both sides: in parts of the valley terraces may be entirely absent on one side or the other (fig. 242, B). In those terraces, on the other hand, which mark the development of flood-plains in brief cycles separated by episodes of uplift there will be perfect accordance of height where terraces are present on both sides, and at some points there may even be perfect symmetry in the width of terraces (fig. 242, C).

Flights of Terraces of Composite Origin.—Many groups or flights of terraces in New Zealand are undoubtedly of composite origin, resulting in part from intermittent uplift, which has certainly taken place, and in part from the effects of restrained down-cutting combined with the protection afforded by gorge-making barriers (figs. 243, 244). This is the case particularly in the valleys of many rivers of the South Island, which are broadly opened where they cross the weak rocks of intermont basins, but contract to gorges in crossing hard-rock barriers farther down-stream. In the North Island similar terraces occur at both ends of the Manawatu Gorge.

C. A. Cotton, photo.

FIG. 244.—Terraces bordering the Waimakariri River, where it emerges from its gorge, Otarama, N.Z.

The Slopes of River Terraces.—All terraces cut by streams have uniform down-valley slopes determined by the stream-gradients at the time they formed part of valley-floors. In the direction across the valley they are practically horizontal, with the exception of some of those developed by lateral swinging, which are lowest at the back, where they abut against the concave fronts of the next higher terraces. The low strip along the back, now generally swampy, marks the last position of the river-channel during a sideward swing, a course from which the river was suddenly withdrawn by a cut-off. Good examples of such swampy strips may be seen on the terraces of the Rakaia River previously referred to.

CHAPTER XVIII.

INTERRUPTION OF THE NORMAL CYCLE BY DIFFERENTIAL MOVEMENT.

Results of tilting of the surface. Ponding. Antecedent drainage. Basin-plains. The law of the migration of divides. One-cycle, two-cycle, and multi-cycle mountains.

Results of Tilting of the Surface. — The results of irregular (differential) movement are in certain respects quite unlike those of the regional movements described in the last two chapters. With differential movement there is deformation of the surface by warping or dislocation by faulting, or perhaps both. Parts may be raised and other parts lowered, level areas may be tilted into inclined positions, and sloping areas may become steeper or less steep, or may have their slopes reversed.

Changes in slope due to warping are not generally of sufficient magnitude to affect hill- or valley-sides appreciably, but where the down-valley slopes of graded streams are altered ever so slightly a regrading of the streams follows and results in characteristic topographic changes.

Streams the channels of which are tilted to a steeper slope are accelerated, and begin at once to degrade throughout the length of the steepened parts of their courses, producing valley-in-valley forms. This rejuvenation, unlike that produced by regional emergence, is not delayed while the head of an inner trench works its way up-stream: it immediately follows the tilting, beginning as soon as the stream flows with increased velocity. Terraces on the sides of valleys rejuvenated in this way, if they are remnants of valley-floors dating from the period before tilting took place, slope down-stream more steeply than the valley-floors developed after the streams are graded again. Where terracing takes place during slow or intermittent tilting the higher terraces slope more steeply down the valley than the lower ones. In New Zealand such terraces

may be seen, for example, bordering the Waiau in the gorge by way of which that river breaks through from the Hanmer Plain to the Waiau–Hurunui Plain (fig. 233).

Graded valleys in which, on the other hand, the down-stream slope has been reduced by tilting or warping begin at once to aggrade in order to restore the graded condition. A considerable amount of aggradation due to this cause has taken place in some valleys between the Rimutaka Range and Port Nicholson, where the surface is sharply warped to form the eastern side of the Port Nicholson – Hutt Valley depression (fig. 170, and Chapter XXIX). The general direction of tilting is towards the west, and all the larger streams flow north or south. Thus the number of streams in which backward tilting might manifest itself is small. Near the

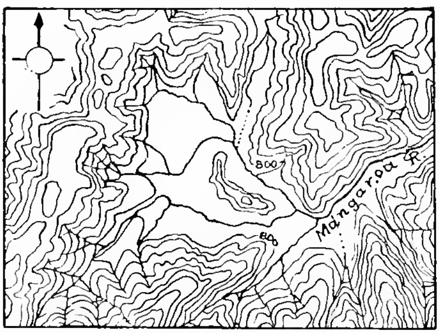
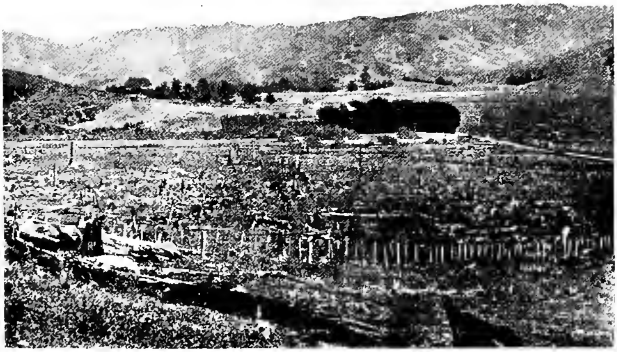


Fig. 245.—Backward-tilted, deeply aggraded tributaries joining the Mangaroa Stream near its head. After map of Manœuvre Area, neighbourhood of Trentham Camp, Wellington, 1915. (Contour interval, 100 ft.)

head of the valley of the Mangaroa (a tributary of the Hutt River), however, a group of tributary streams enters from the west, and the valleys of these are deeply aggraded (figs. 245 and 246), the alluvium even submerging part of the subdividing spur between two of the streams. Similar aggradation, due to the same tilting, occurs in the western branch of the Wainui-o-mata River (figs. 165, 247).

The middle part of a long valley may be gently warped upward, resulting in an increase of slope down-stream from the point where the valley is crossed by the axis of warping and a decrease of slope up-stream from that point; so that down the valley from the



C. A. Cotton, photo.

Fig. 246.—Part of the aggraded area shown in fig. 245. The island-like hill surrounded by alluvium is seen in the middle distance on the left. View looking west.

C. A. Cotton, photo.

Fig. 247.—Another valley aggraded as a result of headward tilting: western branch of the Wainui-o-mata River, Wellington, N.Z. View from the divide at the head of the valley. (See maps, figs. 165 and 170).

axis rejuvenated topography results, while up the valley there is aggradation.

Ponding.—If warping is more pronounced than in the case just cited, and actual reversal of the slope of the valley-bottom takes place for some distance up-stream from the axis of up-warping, the river may be *ponded*—that is to say, a lake may be formed occupying part of the valley (fig. 248, *A*). Thus, when a surface previously eroded is deformed, lakes, in common with rapids and other features characteristic of extreme youth in the cycle of erosion, may appear.

A lake so formed will overflow at the lowest gap, and where the relief is fairly strong and the deformation not very pronounced the lowest gap will generally be along the former course of the river. When the outlet of the lake is cut down through the up-warped arch, and the lake disappears, the drainage of the region in such a case will be much the same as it was prior to the deformation, though for a time there will be topographic evidence that a lake has existed (Chapter XXIX).

If, on the other hand, the relief is weak, or there is a low gap somewhere in the hills bounding that part of the valley in which the lake has been formed (as at *O*, fig. 248, *A*), and if the warping has been pronounced, the lake may overflow along a course entirely different from that followed by the now diverted river prior to the deformation. This new course of the river is consequent on the warping. The stream in the warped valley down-stream from the axis of uplift has been beheaded by warping, and a divide has leaped to a new position. The new course taken by the overflow from the lake will not, in general, fit the river, and the latter will at once proceed to grade it. Such grading usually involves downward cutting, which will lower the level of the lake and, unless its floor has been warped down below local base-level, eventually drain it.

The results are generally similar where warping is complicated to some extent by the occurrence of faults, and, clearly, even without any warping, the formation of a fault-scarp across a river-valley will result in an interruption, and may cause ponding of the river if it faces up the valley.

Antecedent Drainage.—In the foregoing section it was assumed that deformation took place rapidly in order to effect ponding. Such deformation, either warping or faulting, however, sometimes pro-

ceeds very slowly—so slowly that ponding does not take place in the valleys of rivers of considerable size that cross the axes of deformation, even though the slopes of their floors are reversed, or fault-scarps rise across them. A vigorous river is able to maintain its channel by downward cutting across a very slowly rising land-mass, remaining always nearly graded (fig. 248, *B*). Similarly

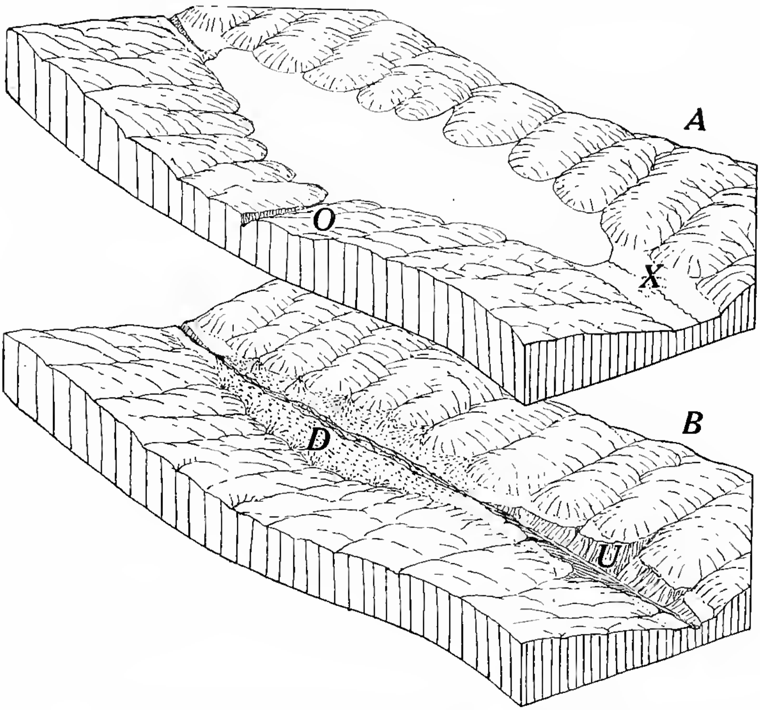


FIG. 248.—Diagrams of the effects of warping transverse to a river-valley. *A*, rapid warping results in ponding; the lake so formed overflows at *O*; the drainage is thus diverted to a new course; and the river formerly occupying the valley is beheaded at the axis of up-warping, *X*. *B*, warping (which may be still in progress) has taken place so slowly that the river has been able to maintain its course by aggrading the down-warped part of the valley, *D*, and cutting a gorge across the up-warped part, *U*.

it will maintain a course across a slowly sinking area by aggradation, building, as it were, a bridge for itself across the depression by depositing alluvium (*D*). In drawing fig. 248, *B*, which

illustrates this point, it has been necessary to compress the warping into a short section of the valley in order to show the effects of both up-warping and down-warping in the same diagram. In nature, however, the axes of depression and uplift are generally much more widely separated.

Such warping may uplift an arch, or faulting may raise a horst or a tilted block, across the line of a river-valley to a height of thousands of feet, and parts of a former valley-floor may be depressed to the same extent. The uplifted areas become mountain-ranges, through which vigorous rivers that have maintained their courses across them as they rose flow in deep, young gorges. Such rivers are termed *antecedent*. Smaller or less vigorous rivers which are unable to degrade as fast as the land rises are ponded and turned aside (as in fig. 248, *A*) into new, consequent courses, and are said to be *defeated*. Many such streams become tributary to their more vigorous neighbours, which thus, as master rivers, carry away the drainage of considerable areas. Reinforced in this way they are the better able to maintain their antecedent courses in spite of further uplift.

A number of New Zealand rivers—*e.g.*, parts of the courses of the Waipara, Hurunui, and Waiau, in North Canterbury—have the appearance of antecedent streams. They make their way in gorges across uplifted blocks, around the ends of which there are comparatively low tectonic gaps that would guide the consequent drainage if the blocks had risen very rapidly or there had been no rivers in existence in the district prior to the deformation. It is thus clear that these rivers are antecedent to at least the greater part of the uplift of the ranges they cross, but it is uncertain whether they took their present courses in a cycle of erosion introduced by gentle uplift and preceding the great deformation to which the present relief is due, or whether they were guided by the first wrinkles of the surface as it emerged from the sea and maintained the consequent courses thus assumed during a continuation of the movements, though in the later, more intense stage of the deformation the shape of the surface changed very considerably and the low gaps do not now coincide with the earliest-formed wrinkles.

The geomorphology of the district may be satisfactorily explained by making either of these assumptions, and if the latter is the correct one the river-gorges are strictly one-cycle instead of

two-cycle features. In that case, therefore, they cannot strictly be called antecedent, but, being consequent on the earlier and antecedent to the later stages of a single series of deforming movements, are termed *anteconsequent* (p. 154) (91, p. 253).

Perhaps the most striking of these antecedent (or anteconsequent) gorges are those by way of which the Waiau and Hurunui Rivers (fig. 249) leave the broad aggraded depression in which Culverden stands (Waiau–Hurunui Plain) and cross an uplifted block, known in part as Lowry Peaks, which presents towards the plain a dissected fault-scarp front rising 2,000 ft. The crest-line of this mountain-block slopes down slightly from both sides towards the Hurunui outlet gorge, which seems to indicate the

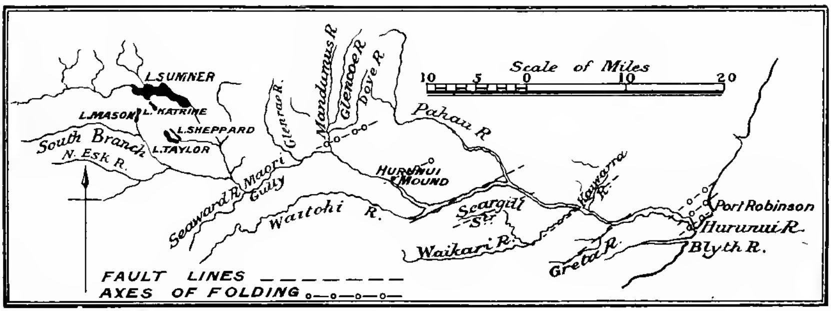


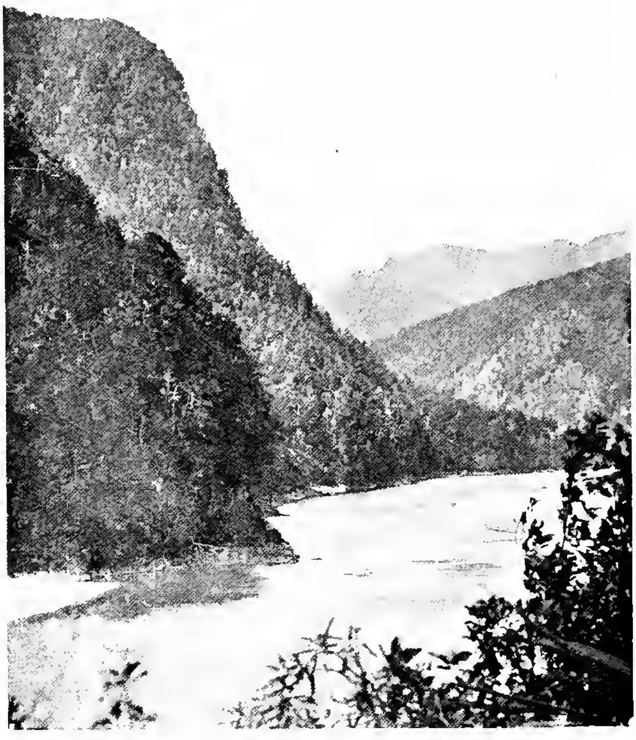
FIG. 249.—The Hurunui River. From the junction of the Mandamus to that of the Pahau the river flows across the aggraded Waiau–Hurunui Plain. Thence to the junction of the Waikari is the main antecedent or anteconsequent gorge. Another, smaller gorge occurs between the Waikari and Greta junctions. (After Speight.)

presence of a sag of the initial surface sufficiently deep to guide a consequent river either during an early stage of the deformation or during a hypothetical preceding cycle.

Down-stream from this great gorge the Hurunui crosses another elongated, though narrower and somewhat lower, uplifted block by way of a gorge of similar origin that is followed by the Christchurch–Parnassus Railway (76, p. 98).

Farther north, in Marlborough, the Clarence River, where it breaks across the northern end of the Seaward Kaikoura Range, appears to be of similar antecedent or anteconsequent origin. If the lower Clarence is a true antecedent river a number of other

streams south of it were, in all probability, defeated by the rise of the massive Seaward Kaikoura block, thus increasing the volume of the consequent river in the Clarence Valley depression behind it; but, if the anteconsequent explanation is the correct



F. G. Radcliffe, photo.

Fig. 250.—The Buller Gorge, cut through the uplifted block forming the Paparoa–Papahaua Range, N.Z.

one, in that case there is no necessity to assume the existence of any such streams.

On the western coast of the South Island some of the larger rivers, such as the Buller (fig. 250), which take direct courses to

the sea by way of gorges cut through recently uplifted mountain blocks, are antecedent,* or possibly anteconsequent.

The lower gorge of the Taieri River is of the same nature, though cut when the land stood somewhat higher than it does now, slight submergence having since allowed the sea to penetrate above the gorge and drown the floor of the intermont depression which has become Waihola Lake.

In the North Island the gorge (fig. 251) by way of which the Manawatu River breaks across from the eastern to the western

F. G. Radcliffe, photo.

FIG. 251.—The Manawatu Gorge, N.Z. View from the eastern side, where the river enters the gorge.

side of the Ruahine–Tararua uplifted mass may be satisfactorily explained as anteconsequent.† The gorge is situated at an uncommonly low sag in the crest of the range.

* P. G. Morgan and J. A. Bartrum, 64, No. 17, pp. 55–56, 1915.

† As explained by Petrie (*Trans. N.Z. Inst.*, vol. 40, p. 290, 1908), this gorge might be either antecedent or anteconsequent. Thomson classes it as antecedent (80).

Basin-plains.—Where warping or faulting, or a combination of the two, takes place on a large scale, aggradation, the beginning of which in a slightly warped valley is shown in fig. 248, *B*, goes on very extensively in the down-warped and down-faulted areas drained by antecedent or anteconsequent rivers through the rising mountain-rims. Alluvial deposits become both deep and wide-spread in these *intermont basins*, and form *basin-plains*—features which are not only characteristic of recently deformed land-surfaces, but must also occur as an accompaniment to the grading of any deformed surface (p. 153). They may thus be associated with either two-cycle or one-cycle topography.

Like piedmont alluvial plains, basin-plains are made up of coalescing fans, every stream that enters the basin depositing its quota of waste as the surface is gradually built up. They are, therefore, made up of a large number of contiguous convex areas, the steepness of which depends on the volumes of the depositing streams and on the coarseness of the alluvium. The complex slopes lead down from either side to the master river, the course of which forms the axis of the basin. This axis is not necessarily central, but may be pushed towards one side of the basin by vigorous growth of the fans on the other side, due, perhaps, to rapid rise of the mountains from which their waste is derived.

A basin-plain formed by deep aggradation over a surface with inherited relief will have an irregular outline, extending in the form of embayments into the valleys of tributary streams, and, even if the surface is plane before deformation begins, valleys eroded on the rising slopes in the early stages of deformation will later become embayments of the plain as the depth of alluvium increases. Where fault-scarps bound the basin, however, their straightness is but little impaired by aggradation, and that little only when movement on the faults has ceased.

Subsidiary blocks or small up-warped areas or ridges of a pre-existing relief may become surrounded by, and even buried beneath, the alluvium of a basin-plain, but, whatever their origin, they are subject to erosion during the deposition of alluvium around them, and so they always underlie it "unconformably."

When earth-movements have ceased, grading of the rivers draining intermont basins results generally in lowering of the outlets, accompanied by dissection and terracing of the basin-plain

deposits, and followed later by extensive planation and perhaps by complete removal of the alluvium if the floor upon which it was laid down is far above base-level.

A small basin-plain at Trentham, near Wellington, N.Z., forms part of the valley of the Hutt River, which traverses it longitudinally (fig. 252). The aggraded depression is of very recent origin, and was formed in the same way, and probably at the same

D. J. Aldersley, photo.

FIG. 252.—View across the basin-plain at Trentham, near Wellington, N.Z., from the fault-scarp forming its north-western boundary.

time, as that containing Port Nicholson, the harbour of Wellington (fig. 170, and p. 238), with which it is almost continuous. It is bounded on one side by the north-eastern prolongation of the Wellington fault-scarp (p. 161). On the south-eastern side, however, the alluvium of the plain embays the valley-bottoms of a surface of considerable relief warped down to form the boundary of the basin.

Splendid examples of basin-plains are found in the Hanmer Plain and Waiau–Hurunui Plain, in North Canterbury, N.Z., the latter unusual in that it is traversed by two main rivers, which break through the mountain-rim to the south-east by way of independent gorges (p. 243). The topography of the North Canterbury district, as noted previously (p. 242), may perhaps be correctly explained as the result of two cycles of erosion; but if, on the other hand, the outlet gorges from the basin-plains are of ante-consequent instead of antecedent origin these basin plains should be classed with the one-cycle forms described in Chapter XII (see

C. A. Cotton, photo.

FIG. 253.—Outlet gorge by way of which the Waiau River leaves the Hanmer basin-plain, N.Z. (See also fig. 233.)

p. 153) instead of with those resulting from interruption of the cycle of erosion.

Both plains are bounded by continuous fault-scarps on the side in which the outlet gorges (fig. 253) are situated, while their other boundaries are less regular. Both seem to have been subject to river planation by their main rivers since the deposition of their alluvium, though small tributary streams have continued to build their fans, and, as is the case throughout this part of the South Island, some aggradation is now again in progress in the main streams. What appears to be evidence of considerable degradation by the main rivers is found in the presence of high terraces bordering

the outlet gorges; but it is possible that the renewed deepening of these gorges is due not to general uplift, but to renewed differential uplift of the mountain-blocks they traverse.

The Central Otago chain of depressions (p. 183, and fig. 161) may be regarded as basin-plains in which the alluvial accumulations have long ago been dissected and then removed by planation following the deepening of the outlet gorges. The small relief of the existing floors of these depressions is due to the weakness of the rock formation underlying them (p. 130; figs. 131, 150).

The Law of the Migration of Divides.—Where two streams heading opposite to each other and flowing in opposite directions —*e.g.*, subsequents on the same outcrop of weak rock—are affected by an even lengthwise tilting movement, that one whose slope is steepened cuts downward vigorously and grows in length by headward erosion at the expense of the other, pushing the divide between them up the tilted surface. If the tilting is part of a general warping, the divide migrates towards the axis of up-warping.

The effect of even very slow warping of a land-surface is thus to cause divides to migrate towards the axes of up-warping, with which eventually they must approximately coincide, while, conversely, streams shift towards and tend eventually to coincide with the axes of down-warping (Campbell, 26, pp. 580–81). The general law that axes of up-warping becomes divides is, of course, subject to exception where uplifted arches are crossed by antecedent rivers.

The rejuvenation by tilting of subsequent streams flowing in one direction, and their resulting activity in headward erosion, leads to frequent captures of transverse streams, and thus warping may greatly accelerate the process of adjustment to structure.

One-cycle, Two-cycle, and Multi-cycle Mountains.—In the older classifications of mountains "fold mountains" figured prominently, and in that class were placed all mountain-ranges composed of folded rocks. As used by geographers the term "fold mountains" implied that the uplift initiating the erosion to which the present relief is due accompanied the compressive movements of which evidence is found in the folded structure of the rocks.

The initial form of such a range must be a huge pile of crowded, squeezed, and broken arches of rock. At a later time the limits of the range, though not its height, might be

expected to correspond with the limits of the whole *geanticline*, or composite arch, but no agreement need be looked for between the surface forms of individual arches and the details of the mountain-peaks; for erosion is extremely rapid among mountain-peaks, bare-rock surfaces abound, frost-action is vigorously at work, and steep slopes lead the broken waste downhill as talus, which is presently delivered into mountain torrents and swept away. Indeed, it appears certain that a range with a highly accidented initial surface would be maturely dissected while still in its period of vigorous growth, and long before it had attained its maximum height.

Not many years ago all the great mountain-ranges of the world which are built of folded rocks were believed to have originated as "fold mountains," and to be now in process of reduction by erosion for the first time; for it was recognized that erosion must reduce their height, round off their peaks, and ultimately destroy their relief. In the language of geomorphology, the mountains were believed to be undergoing erosion in a cycle introduced by the uplift accompanying or resulting from folding. To put it in another way, they were *one-cycle* mountains.

The absolute length of a complete cycle (the time required for the destruction of a mountain-range) is unknown, and even its relative length as compared with intervals of geological time is but vaguely understood. Moreover, it varies enormously with different kinds of mountain-forming rocks, and in different climates. While, however, the immensity of geological time is being more clearly realized, the efficiency of subaerial erosion and the comparative brevity of the cycle of mountain-destruction are becoming more apparent; and the intervals since the geological dates of the folding in many ranges, though formerly regarded as brief, seem now more than sufficient to allow of the dissection and reduction of the mountains to their present state.

In many parts of the world evidence has come to light also which proves that mountain-ranges are really dissected plateaux, though composed of folded rocks (p. 123). They are *two-cycle*, or perhaps *multi-cycle*, mountains, the region having been since the folding worn down by erosion to small relief at least once, and possibly more than once, prior to an uplift, generally a broad up-warping, which was followed by deep dissection of the plateau so

formed. Mountains that have originated in this way are recognized owing to the preservation of some remnants of the plateau from which they have been carved. The initial form in this case, having a comparatively level surface, is not so quickly eroded away as the tumbled crest of a pile of folds. Those parts of it that are evenly uplifted are encroached upon little by little as dissection of the highland proceeds, a few remnants far from the principal rivers perhaps surviving long after other parts of the region have been completely dissected to a sea of sharp ridges and peaks. It is justifiable to suspect that other mountain-ranges in which plateau-remnants no longer survive have also had a multi-cycle origin, and this suspicion often receives a considerable amount of confirmation from an accordance of summit-levels (p. 125) which suggests the restoration of a vanished plateau a little above the present summits of numerous peaks of nearly even height.

A list of the important mountain-ranges that have gone through more than one cycle of erosion would be so long that it would make tedious reading, but it may be mentioned that even the Jura Mountains, so often referred to as an example of a system of rock-folds not yet destroyed by erosion, are now known to have been reduced to small relief, uplifted, and redissected.

It is quite conceivable that the mountains formed by the original folding on the sites of some of the great ranges of the present day were of relatively insignificant height. The piling-together of rock-folds does not necessarily form a great protuberance on the earth's surface, for the lithosphere, or "crust," is not rigid, but yields under a load; and so the folded rocks may sink until isostatic equilibrium is restored, a place being made for them by lateral flow of deeply buried rocks. As to the cause of the broad upswellings of the surface that have taken place later, and have led to deep dissection and the sculpture of mountains, nothing is known with certainty.

Sometimes the renewed uplift of worn-down fold mountains has been accompanied by much faulting, with the formation of block mountains (Chapter XII).

CHAPTER XIX.

ARIDITY, AND THE WORK OF WIND.

Aridity, a climatic accident. The arid cycle. Modifications of the normal cycle due to semi-aridity. Wind as an eroding agent. Wind-work in deserts. Sand and dust transported by wind. Deposition of sand. Drifting sand. Forms of dunes. Fixation of dunes. Partial fixation leads to irregularity of dunes. Ancient blown-sand deposits. Loess.

Aridity, a Climatic Accident.—One of the climatic accidents previously referred to which may bring the cycle of normal erosion to a close is a change to aridity. Should this change take place, the topography — young, mature, or old — developed under pre-existing humid conditions would furnish the initial forms from which would be developed a topography characteristic of arid conditions. The initial forms in a cycle of arid erosion may, on the other hand, be produced by deformation or dislocation, as in the case of the normal cycle.

The Arid Cycle.—A full discussion of the arid cycle as pictured by Davis (4, pp. 296–322) or by Lawson (55) would be out of place here, for there is no reason to believe that erosion under really arid conditions has been responsible for the sculpture of any part of the New Zealand area. It will suffice to indicate some points of divergence of arid from normal erosion.

Even in the most arid deserts rain does not fail altogether. There are no permanent rivers,* but intermittent streams resulting from the heavy showers of rain which occur at long intervals move great quantities of waste. Thus in the arid cycle the work of running water cannot be left out of account. The general base-level, however, has not the importance that it has in the normal cycle as a level towards which the surface tends to be lowered. The streams do not join up to form rivers flowing

* Permanent rivers, such as the Nile, rising in humid regions and flowing through deserts, introduce special conditions that need not be touched upon here.

to the sea, but dwindle, deposit their waste, and perhaps sink altogether into the alluvium-covered ground; or the diminished streams may flow farther and discharge into lakes occupying the lowest parts of depressions. Evaporation, which removes a volume of water proportional to the free surface, prevents such lakes from growing large enough to spill over and form integrated systems of drainage. Their waters become concentrated solutions of salts, and, generally, in dry seasons they dry up altogether, leaving plains of saline silt. These shallow, inconstant salt lakes are termed *playas*. A lake of this kind forms a temporary base-level for the area that drains into it, but this is a base-level that rises as waste accumulates in the basin; and the base-levels of separate basins are entirely independent of one another.

In regions of strong initial relief (such as the Great Basin province of North America) under arid conditions there is an enormous development of alluvial fans, forming vast piedmont or basin plains, the slopes of which lead down to the level of playa lakes. In the early stages at least of the cycle each initial depression has its independent centripetal system of drainage, though later, as some depressions become filled with alluvium, spilling-over of waste, and with it of water, from one basin to another may occur, so that integration of drainage may take place to a limited extent.

The alluvium of the fans is derived from the surrounding mountains, the fronts of which retreat as steep, ragged, ungraded slopes until they finally disappear, and the alluvial-fan slopes reach to the range-crests.

Modifications of the Normal Cycle due to Semi-aridity.—Regions which have a scanty rainfall—just sufficient to maintain an integrated drainage-system capable of transporting the waste supplied to it, but insufficient to promote a continuous covering of vegetation on the surface—may be described as semi-arid.

As there is neither forest nor a continuous sward of grass, but instead merely a discontinuous covering of scrub or tussock-grass, the conditions of equilibrium on slopes are not the same as in normally humid regions. Slopes when graded and stable are less steep, for the superficial waste is liable to be washed off, and talus slopes are common even on hillsides that have been reduced to a rather gentle slope. As a thick waste-mantle cannot

accumulate at an early stage, outcrops of bare rock persist longer. Thus somewhat ragged, ungraded, hill profiles persist far into the mature stage of the cycle. In New Zealand this is the case in Central Otago (fig. 254).

Where there are alternations of fairly thin beds of hard and soft rocks on hill or valley sides erosion tends to etch these into flights of steps, or *structural terraces*, steeper slopes marking the bare outcrops of the harder rocks and gentler slopes of moving talus covering the softer outcrops. Under humid conditions such features are shorter-lived, being confined to an earlier stage of the

C. A. Cotton, photo.

FIG. 254.—Ungraded, though nearly flat, surface of the Raggedy Range, Central Otago, N.Z., the result of erosion in a semi-arid climate.

cycle, and so they are found less commonly. They fade owing to rounding-off of the edges when the accumulating waste is bound by vegetation and its movement is restricted to creep—in other words, when the surface becomes graded.

Another effect due to the absence of protective vegetation is the development of badland topography (see p. 35), especially on clay outcrops, for the bare ground is exposed to the erosive action of falling raindrops, and the run-off is excessive owing to the absence of an absorbent soil-covering.

During the early stages of the cycle under semi-arid conditions there is a great development of accumulation forms. The supply of waste from the poorly protected surface is considerable. The streams, however, being of small size, are capable of transporting this material only down steep declivities. Thus abundant fans of rather steep slope are built in all depressions of the initial surface, and these may coalesce to form broad piedmont and basin plains. As the thickness of alluvium increases, aggradation extends up the valleys into the mountains. The alluvium may overtop divides and isolate portions of the mountain-masses, and a system of basin-plains may be united by the spilling-over of alluvium from one to another, so that perhaps half the region may become a plain of aggradation.

Such alluviation will not proceed as far, however, as does alluviation under arid conditions, for, where a normal drainage-system is developed and maintained, fans and aggraded plains will cease to grow when the supply of waste falls off as a result of lowering of relief and reduction of the area subject to degradation. As the supply of waste continues to diminish and the cycle proceeds farther the aggraded surface will be gradually cut down by stream planation. At this stage, which may be seen in New Zealand in the great basin-plain of the upper Waitaki, or Mackenzie Plain, considerable remnants of the maximum fans form terraces bordering valley-plains of gentler slope cut in the alluvium.

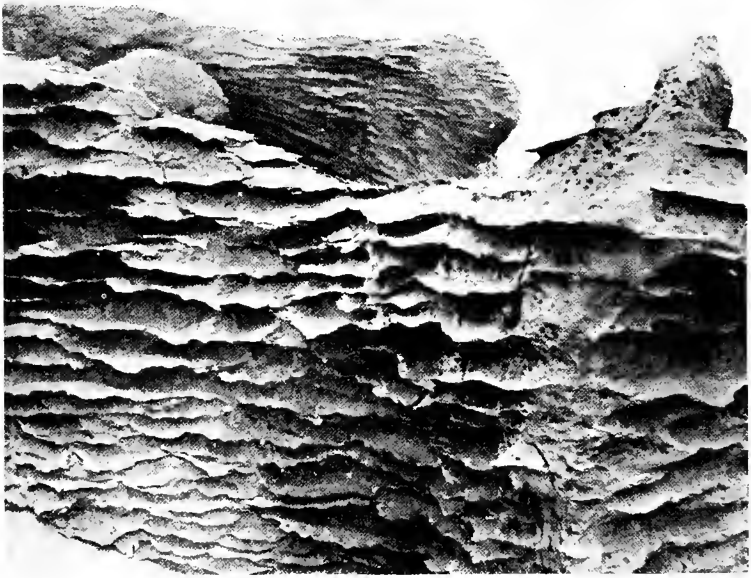
Continued erosion will result in removal of all the alluvium that lies well above the local base-levels determined by lines of main drainage, leading to a stage illustrated in New Zealand by the (relatively) lowland areas fringing on the south the northern highland of Otago, and forming the Maniototo Plain and the Ida and Manuherikia Valleys (figs. 186, 187), where the slopes of the valley-plains and the terraces that border them—all cut on soft bed-rock* — are so steep on account of the high ratio of waste to water in the streams from the northern highland that they resemble fans.

When, eventually, the mountains in such a region are worn down, and so the supply of waste becomes reduced to almost nothing, all stream-declivities will become gentle, and a normal peneplain will result.

* The "covering strata" of Chapter XI.

Wind as an Eroding Agent.—Wind is not in itself an active eroding agent, but it is able to wear away rocks by means of dry sand which it carries.

In a humid climate the work of wind is unimportant as a component of weathering or in the sculpturing and general lowering of the land-surface, for, except in some river-beds and along the seashore, there is not a supply of loosened fine waste available for use as a corrading agent. The rocks and the waste-mantle are also



L. Cockayne, photo.

FIG. 255.—Rock-outcrop etched into relief by the action of wind-borne sand, which has cut away the softer layers of rock.

protected from wind erosion by the covering of vegetation. In an arid climate, on the other hand, owing to the absence or the scattered nature of the vegetation, not only is there a supply of dry waste, but also a large area of partially weathered or fresh rock is exposed, and is therefore subject to attack by wind that sweeps waste over it.

Because of its generally humid climate, no part of New Zealand affords examples of the erosive work of wind excavating, carving, or modifying large topographic forms. On many parts of the coast, however, a considerable supply of dry sand is blown inland, and some also is blown out of the beds of South Island rivers, especially in the dry parts of Otago and Canterbury. Where such blown sand occurs, its scouring effects on rock-outcrops may be looked for (fig. 255).

Fine dust carried high in the air is of very little importance as an abrading agent, but erosion is effected by coarser material, generally fine enough to be classed as sand, which is swept along close to the ground. A particle of this sand has a sufficiently large mass to strike an effective blow when blown against solid

C. A. Cotton, photo.

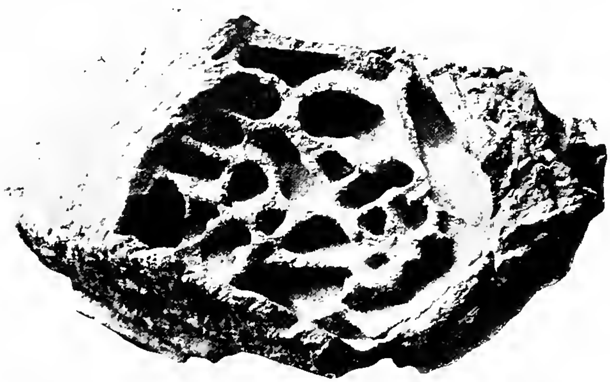
FIG. 256.—Faceted pebble from the sand-dunes at Lyall Bay, Wellington, N.Z., etched by wind-blown sand. Viewed from above. Natural size.

material, and a constant stream of sand-grains wears the material away just as rocks in a stream-bed are worn away by the passage over them of water-borne waste.

Since coarse material is not generally lifted more than two or three feet, wind erosion is effective only close to the ground. Thus cliffs may be cut away at the base, with the result that the unsupported upper parts slip down. For a time the accumulation of fallen material, forming a talus slope, protects the base of the cliff from further undercutting; but the fallen blocks will be themselves attacked, and may eventually be completely reduced to

sand and dust and removed, for the transporting power of wind is practically unlimited. The sand and dust resulting from abrasion do not accumulate so as to check further erosion, but are blown away to accumulate elsewhere.

Proof of the corrasive power of wind-borne detritus is to be found where pebbles lie in the track of drifting sand. These are sometimes found to have flat faces, or facets, cut upon them, facing prevailing wind-directions, frequently two well-defined facets meeting in a sharp ridge along the top of a pebble. Such faceted pebbles are found not only in deserts, but also in humid climates near the seashore—*e.g.*, at Lyall Bay, Wellington, N.Z. (fig. 256).



C. A. Cotton, photo.

Fig. 257.—Honeycomb weathering of rock from an outcrop near the seashore, Wellington, N.Z.

Wind is effective also in removing sand from the cells formed in the peculiar process of *honeycomb weathering* found in some deserts and sometimes also near the seashore in humid regions—*e.g.*, in greywacke rocks near Wellington, N.Z. (fig. 257). The walls of the "honeycomb" cells are strengthened by a mineral deposit containing apparently a good deal of iron oxide, which is deposited along the walls of closely spaced joints. The mineral matter so deposited is evidently leached from the intervening areas, where the sand-grains are loosened by weathering, so that they are readily removed by wind. It is possible that the chemical actions involved in the leaching and deposition of the mineral matter forming the

cell-walls is due to salt supplied by sea-spray, or, in deserts, blown from playas.

Wind-work in Deserts.—In desert regions which retain considerable relief, if the rainfall is by no means negligible, as in the Great Basin province of North America, referred to previously, wind-work is of only minor importance, and wind may be left out of account as a factor in determining the broad features of relief. In some desert regions, however, wind is recognized as playing a greater part among the erosive agents, owing, perhaps, to extreme aridity, as in parts of Africa; to the nature of the rocks; or to the insignificant measure of the initial relief, as in Western Australia (where wind-work has been described by Jutson, 54).

Where either the fragments produced by mechanical disintegration of rock-surfaces are sufficiently fine to be removed by wind, or coarser waste is produced at so slow a rate that it can be reduced to sand and dust by the abrasion of wind-borne sand and then blown away, the profiles of residual elevations in the desert are strikingly different from those in the American deserts previously referred to. Fans and large talus slopes are absent, and their absence is thus a characteristic feature of dominant wind erosion.

Residual elevations are gradually reduced in size as the escarpments or cliffs that bound them retreat, leaving wind-scoured flats. Wind erosion is capable of cutting the surface down to a horizontal plane governed by the local level of the water-table, for when this is approached the ground becomes damp as water rises to the surface by capillarity, and only dry material is at the mercy of the wind. Subject to the limit set by the level of ground-water, wind is capable of lowering the whole surface of a desert region by complete removal of material in the form of fine dust, which is whirled high into the air and carried beyond the limits of the desert. The supply of dust to be exported thus is kept up in part by the abrasive action of sand on rock-outcrops and on larger fragments, and in part also by mutual attrition of sand-grains as they are blown to and fro over the desert plains.

Sand and Dust transported by Wind. — Wind is capable, as previously noted, of transporting sand, which is swept along close to the ground, and dust, which is carried high in the air. Sand-grains move forward by a series of short leaps, whereas dust-particles may travel distances of many miles without falling to the

ground. It is thus clear that when a mixture of sand and dust is dry and is subject to transportation by wind the dust is rapidly blown far away, leaving a residue of clean sand. Dust produced by the wear of grains of blown sand on oue another is likewise removed by this winnowing action of the wind.

Clean sand may be winnowed from the products of desert erosion or from the silt spread by a flooded river. Sand of rather even grain is thrown up on beaches by the sea, and may, if it becomes dry, be blown inland in considerable quantity. Such sand has already been separated from finer particles, as well as from coarser fragments, by the sorting action of waves. It is composed of grains of the most resistant minerals of disintegrated rocks, the most abundant of which in white sand is quartz, and in black sand magnetite.

Though all sand-grains, whether originating from rock-disintegration on land or derived from the sea, are angular to begin with, when blown about by the wind they suffer attrition, their angles are rounded off, and they become almost spherical, thus contrasting strongly with the persistently angular sand-grains which result from the grinding of waste in water—either in rivers or the sea. In water, sand-grains, unlike the larger fragments which become rounded pebbles, are protected from abrasive contact with one another by films of water which adhere to them by surface tension and form effective shields against the blows struck by such small masses. Dry sand-grains driven by wind, however, have no such protection.

Deposition of Sand.—Since sand and dust are so effectually separated by the action of wind, it is not surprising that they should be deposited in different situations under widely different conditions. Much of the dust, indeed, is scattered far and wide. Some falls into the sea and some is washed out of the atmosphere by rain or, having fallen to the ground, is washed away into streams. It is only under special circumstances (referred to below) that dust forms accumulations on the land. Sand, on the other hand, may accumulate not far from the source of supply, though some is blown and washed into rivers and into the sea. Moreover, dry sand accumulations on the land, like deposits of alluvium, are liable to be short-lived unless lowered by earth-movements below base-level and thus placed beyond the reach of erosion.

Drifting Sand.—A constant supply of sand carried forward by the wind—*e.g.*, from a beach—may result in its spreading as a thin sheet over a considerable area of country. A mere sheet of sand results, which is not a conspicuous topographic form, as the layer of sand conforms fairly closely to the pre-existing form of the surface. Sand-drifts, however, ruin much good agricultural land; and owing to destruction of the vegetation on the ground over which the sand passes, where sand-drifting temporarily occurs, sand hitherto held in place by vegetation is left at the mercy of

L. Cockayne, photo.

FIG. 258.—Formerly grass-covered river terrace converted into a stony desert by sand-drift, Tarras, Central Otago, N.Z.

the wind, which hollows out and variously modifies the surface, and carries away the sand to redeposit it somewhere else.

A sand-drift hundreds of acres in extent and of quite modern origin extends across Otago Peninsula, N.Z., near Taiaroa Head, The sand is derived from sandhills on the shore of Otago Harbour, where it was held in place by vegetation until disturbed by rabbits. The drift now extends over a saddle and descends to the seashore on the outer coast.

L. Cockayne, photo.

Fig. 259.—Crest-line and sandfall of a wandering dune, western Wellington, N.Z.

W. H. Field, photo.

Fig. 260.—A fore-dune bordering a shore-line that is advancing owing to accumulation of sand, Waikanae, N.Z.

In parts of semi-arid Central Otago sand-drifts have swept over large areas of gravelly valley-plains and terraces, completely destroying the vegetation and converting them into stony deserts when the sand, and with it the unprotected soil, have been blown away (fig. 258).

Forms of Dunes.—Sand transported by wind accumulates frequently in hillocks or ridges termed *dunes*. Some slight obstruction, generally a tuft of vegetation, causes the bottom layer of wind to lose velocity and to deposit the sand which it is sweeping along close to the ground. Thus a small hillock is formed which itself acts as an obstruction, and so sand which is carried over the crest is continually deposited in the lee of the first accumulation, until the hillock grows into a dune of perhaps a hundred or even several hundred feet in height. In New Zealand "20 ft. to 50 ft. is a common height, but hills of 100 ft. and more are not infrequent" (Cockayne, 28).

The sand on the slope facing the wind does not remain undisturbed, but whenever the supply from farther back falls off, so that the wind sweeping over the dune is not fully loaded, it picks up sand and carries it over the crest, only to drop it again as a new layer on the leeward side. Thus a dune moves slowly forward, and where the supply of sand is intermittent a small dune or group of dunes may travel forward, leaving the ground bare behind them.

The leeward side, or "sandfall" (fig. 259), of a dune, on which the sand comes to rest when dropped by wind as it comes over the crest and loses velocity or forms an eddy, has a steep slope, generally about 30°, that being the inclination at which the streaming sand comes to rest. The slope of the windward side, up which the sand is driven by the wind, is much less steep. This side is generally "ripple-marked"—that is to say, there is on it a pattern of small ridges a few inches apart, which travel forward just as dunes do.

Other conditions being the same, low dunes or the low parts of dunes move forward more rapidly than high parts, as they use up less sand in advancing a given distance. Thus short dunes become crescentic in outline, as wings at the sides move forward in advance of the centre, and the crest-lines of elongated dunes become sinuous. Such forms are often obscured, however, by the effects of strong winds blowing successively from different directions.

Coastal dunes are found chiefly on low-lying land recently abandoned or built up by the sea (Chapters XXVII, XXIX). On such coasts, where the waves are throwing up sand abundantly on the beach, much of the sand, when it dries, is blown inland. In a humid climate like that of New Zealand, however, it is arrested by vegetation before it has travelled far, and forms a ridge, or *fore-dune*, parallel with the shore-line (fig. 260). The plants which arrest sand thus and cause it to accumulate in ridges or dunes (sand-binding plants) are those which can remain alive and grow upward vigorously though their original roots are deeply buried. As the sea retreats, a succession of *dune-ridges* may be thus built, each in its turn being the fore-dune. While these are growing they are fairly even-crested and have smooth slopes towards the sea, while landward the sandfall slopes may be somewhat irregular, salients projecting where sand has come over the crest in the largest quantities. The older dune-ridges, however, unless rapidly and permanently fixed by a cover of vegetation, are "most irregular in form, and much cut into and denuded by the wind. . . . These chains of hills resemble miniature mountain-ranges with their prominent or rugged peaks, rounded tops, saddles, deep or shallow gullies, and at times quite precipitous faces. Frequently the parallel chains have lateral connections. Near the coast they are generally but semi-stable, the plant covering usually only occupying half their surface, and in many places they are so bare as to be a transition to the wandering-dunes" (Cockayne, 28).

Wandering dunes (fig. 259) "are broad, high masses of sand extending over many acres, so gently sloping on the windward side as to be apparently flat in places, where they are quite firm to the tread. On the leeward side they are very abrupt—so much so, where absolutely sheltered from the wind, as to merit the title of 'sandfall,' the extremely loose sand moving with the slightest touch. . . . At the angle formed by the ascending slope and descending sandfall is often a sharp ridge, the result of the eddy [fig. 259]. In other cases the angle may be rounded, a sign of contrary winds" (Cockayne, 28). In New Zealand "the wandering dunes as now met with inland . . . are a *reversion* from perfectly fixed sandhills [see below], held in position not only by shrubs or grass but by loam, to the original wandering state" (Cockayne, 28).

Barchans are isolated mounds of sand travelling forward as dunes with the crescentic form previously explained. Small barchans have been noted in New Zealand at Alexandra, Central Otago (Cockayne, 28).

Fixation of Dunes. — Where dunes accumulate in a humid climate they are always more or less fixed by the growth of vegetation on them, and such fixation may become complete, the vegetation becoming quite continuous and resulting in the formation of a layer of soil rich in humus. Large areas of coastal dunes in

L. Cockayne, photo.

FIG. 261.—Naturally fixed dune-ridge carrying a crop of oats, western Wellington.

New Zealand, especially in western Wellington, are thus fixed, and in some cases the original forms of the coastal dune-ridges are preserved (fig. 261), and it is certain that the area of fixed dunes was much greater before the disturbance of the vegetation and surface caused by man and introduced animals started sand-drifts which have resulted at many places in the formation of wandering dunes.

Thoroughly fixed sand-dunes in a humid climate form the initial surface for a cycle of normal erosion. The loose sand of

W. H. Field, photo.

Fig. 262.—Wind-channel among sand-dunes, western Wellington, N.Z.

T. L. Lancaster, photo.

Fig. 263.—Small lake in a valley blocked by a wandering dune, near Te Henga, west coast, Auckland, N.Z.

dunes offers very little resistance to normal erosion, but this lack of resistance is to a great extent offset by the porosity, which reduces run-off to a minimum. Below the level of ground-water the sand becomes cemented and its porosity is reduced. In all cases the chaotic dune topography, with its irregular hollows, must be replaced sooner or later by systems of continuous valleys, with graded streams and graded slopes, and this eventually must become a peneplain. In New Zealand large areas of partly indurated sandstone on the west coast of the Auckland province, which

L. Cockayne, photo.

FIG. 264.—Advance of wandering dune stopped by the Turakina River, western Wellington, N.Z.

accumulated as dunes, now display topographic forms due to normal erosion only.

Partial Fixation leads to Irregularity of Dunes.—Without complete fixation taking place sand-binding plants grow in irregular patches on accumulating and migrating dunes, with the result that the dunes lose all regularity of form. Sand accumulates around clumps of vegetation, forming irregular hillocks, and, when the supply diminishes, some sand is scoured away from spots that

remain bare. Saddles and gullies are thus hollowed out of the dune-ridges, cutting these into rows of irregularly shaped mounds (fig. 262). Eddies of the wind on such an irregular surface build also irregular accumulation forms.

When the supply of sand from windward fails the dunes may be completely blown away over considerable areas, *sand-plains* being formed, where the lower limit of erosion is governed by an approach to the level of ground-water (Cockayn , 28). These persist, perhaps clothed by vegetation, until obliterated by a fresh invasion of sand and replaced by dunes.

The various types of dunes—accumulating, fixed, and in course of destruction—with sand-plains and ponds, lakes, and swamps caused by the blocking of streams, make up the *dune-complex* (Cockayne, 28).

Small streams are frequently blocked by sand-drift or dune-migration, forming shallow lakes, such as the Horowhenua Lake, in western Wellington, and many small lakes in various parts of New Zealand (fig. 263); but where a river of considerable size crosses the dune-complex it may be capable of transporting all the sand spilled into it. Such a river forms an effective check to the migration of dunes (fig. 264).

Ancient Blown-sand Deposits. — Blown sand sometimes forms permanent accumulations, which are analogous to alluvial deposits laid down where aggradation is in progress. The supply of sand may be so great that the level of the land must be to some extent built up by it. Individual dunes march forward, but all the sand at the base does not move on. Thus the stump of the dune remains, and where accumulation is in progress the resulting deposit consists of the stumps or bases of innumerable dunes, each roughly lenticular in shape, and each built of inclined layers, which are sometimes very distinct in cuttings through blown-sand deposits.

This inclined stratification, to which the name *cross-bedding** is given, is the result of the manner of growth of sand-dunes previously described. The layers are successive additions to the sandfall slope, and they are distinguished by slight variations in the coarseness of the sand in successive layers, due to variation in the velocity of the wind during their accumulation.

---

* Cross-bedding, though generally on a smaller scale, is found also in sands and gravels deposited in river-beds and shallow seas.

Deposits of blown sand, now compacted into a soft sandstone, which is generally brown owing to oxidation of iron compounds in the sand, outcrop over large areas at various places on the western coast of the North Island. In other parts of the world very ancient deposits of similar origin occur, which owe their preservation to their being lowered below base-level.

Loess.—The fine dust which is carried high in the air, and if dropped is readily picked up again, does not come finally to rest

A. C. Gifford, photo.

FIG. 265.—Cutting revealing a thick deposit of loess, Oamaru, N.Z. The subdued hill forms of the loess-surface are seen above.

in arid regions, but is exported from them. Some of the dust from deserts, however, and also some of that derived from river-beds is caught by grass in more humid regions. The grass continues to grow up through the slowly accumulating dust. This is the source of great accumulations of superficial yellow clay known as *loess*. Loess covers large areas in various parts of the world, notably in northern China, where it is in places 300 ft. thick. It occurs also in northern Europe, in North America, and

in New Zealand, particularly on Banks Peninsula, on subdued hills about Oamaru and Timaru, and in Southland.

There is no distinct stratification in loess, but there is an indistinct vertical structure of a kind of tubes strengthened by a deposit of carbonate of lime. The loess is thus strengthened so that it stands with vertical walls in cliffs or cuttings (fig. 265). It is not, however, really a hard stony substance, but may be easily powdered with the fingers. It is remarkable for the extreme fineness of all the mineral grains in it. These are fragments of ordinary rock minerals and weathering products. Substances necessary for plant-growth are in an available form, and loess furnishes, therefore, an extremely fertile soil.

Much of the loess in New Zealand is thought to have accumulated when the glaciers of the South Island were more extensive than at present, and when the rock-flour produced by glacial erosion was carried out beyond the mountains in large quantities by the ice-fed rivers, there to be spread out at times of flood and afterwards distributed by the wind. Great quantities of dust are still carried across the Canterbury Plain by north-west winds, however, and so the accumulation of loess must be regarded as still in progress.

Accumulation of loess does not affect topography to any great extent, as it is distributed impartially by the wind over hills and valleys. Loess deposits are, however, very easily dissected and reduced to subdued relief. Much loess is carried down from hill-sides by streams and deposited in low-lying areas, mixed with coarser waste derived from underlying rocks, as river and lake deposits.

CHAPTER XX.

GLACIERS.

Snowfields and glaciers. Mountain-and-valley glaciers. Glacier ice. The flow of glaciers. Crevasses. Moraines. Lower limits of glaciers. Ice caps. Piedmont glaciers.

Snowfields and Glaciers. — Apart from the effects of frost-action as a component of ordinary weathering in shattering rocks by alternate freezing and thawing in crevices, it is in the form of glaciers that ice exerts, and has exerted, its most important geological action. *Glaciers* are streams of ice flowing, as rivers do, from higher to lower levels, though infinitely more slowly than rivers, taking their rise in snowfields, and thus carrying off the snow that falls on high mountains, and also at lower levels in polar regions, where the annual precipitation as snow is in excess of the amount disposed of by summer melting. Above the " snow-line," the height of which above sea-level varies from zero in the polar regions to about 17,000 ft. near the Equator, snow lies from year to year, forming permanent snowfields (fig. 266). Such snow-fields, or *névés*, themselves, whether they give rise to definite, elongated ice-streams (*glacier-tongues*) or not, are to be regarded as glaciers, or as parts of glaciers, and part of the erosion ascribed to glacial action is due to them—some of it, apparently to normal processes working in close association with them, as will be explained below.

At the present day glaciers are acting as corrading and transporting agents, but (outside the polar regions) only in restricted areas. In spite of the restricted occurrence of glaciers, however, the ways in which they modify topographic forms, and also the form and structure of the materials deposited by them, are worthy of detailed study, for at various times in the past glacial action, or *glaciation*, has been in operation over very much wider areas than at the present day, large regions having been at these

times overswept by ice. The latest of these "glacial periods" came to an end so recently that the topographic features resulting from the erosive action of the glaciers and the deposits of superficial material left by them have been very little modified since by normal erosion.

There is a great difference between the discontinuous glaciers found in regions of high relief and the continuous *ice sheets*, or *ice caps*, which are now restricted to polar regions, but which in glacial periods partially covered the continents. The former exist

F. G. Radcliffe, photo.

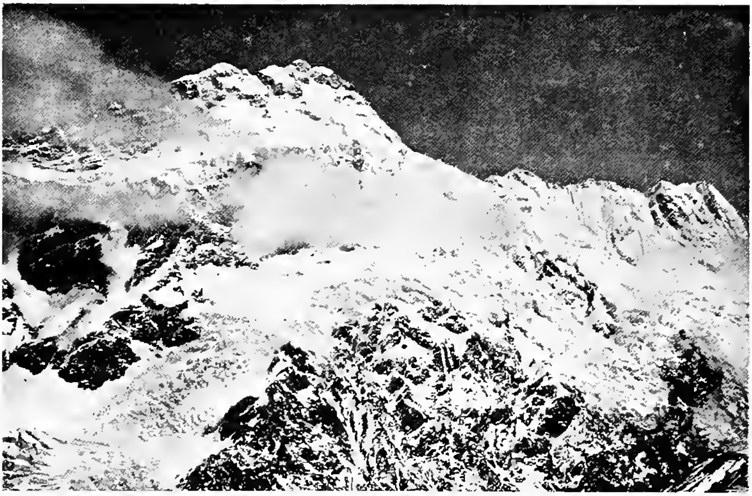
Fig. 266.—Mountains rising above the "snow-line," the Minarets, Southern Alps, New Zealand.

in New Zealand to-day (fig. 267), and have played an important part in the development of the relief features of some districts. They will be considered first.

Mountain-and-valley Glaciers.—Glaciers found now in mountainous districts may be divided roughly into *valley glaciers* and *hanging glaciers*. In the former the ice originating in a névé (figs. 267, 269, 272) flows as an elongated stream or tongue far down a valley (figs. 267, 270, 271), and, especially if its volume is

FIG. 267.—Glaciers of the Southern Alps, New Zealand. (After Marshall.)

1. Hochstetter Dome.
2. Élie de Beaumont.
3. Mount Green.
4. Mount Darwin.
5. Malte Brun.
6. Mount de la Bêche.
7. Mount Haidinger.
8. Mount Haast.
9. Mount Tasman.
10. Mount Cook.
11. Mount Hicks.
12. Mount Stokes.
13. Mount Sefton.
14. Mount Sealey.



F. G. Radcliffe, photo.

FIG. 268.—Hanging glaciers on Mount Sefton, Southern Alps, New Zealand, showing also two avalanches falling (on the left).

F. G. Radcliffe, photo

FIG. 269.—Head of the Tasman Glacier, New Zealand.

augmented by the confluence of *secondary glaciers* (smaller glaciers of the same kind joining it as tributaries) and by falls of snow and névé ice (*avalanches*) from the valley-sides, may push its way down far below the snow-line, until eventually, unless in a high latitude, it dwindles and disappears owing to melting. Hanging glaciers are smaller, and consist practically of the névé portion only. The névé accumulates in a shelf-like hollow on the mountain-side, from the edge of which there is a steep descent to a valley. A hanging glacier may completely fill its niche (fig. 268), and in this case the ice as it moves forward breaks away at the edge, falling as avalanches down the steep slope beyond to melt in the valley below or to swell the volume of a valley glacier there.

The distinction here made between valley glaciers and hanging glaciers is not a sharp one, for instead of discontinuous avalanches a steeply-sloping, rugged tongue of broken ice—an *ice-fall* (p. 279)—may be formed where the ice from the high névé pushes its way over the edge of its niche (fig. 274). Also it is clear that some hanging glaciers of the present day are the shrunken remnants of former valley glaciers.

A hanging glacier as a whole is homologous with the head of a valley glacier. Below this névé portion the glacier-tongue, or ice-stream, of a valley glacier is often narrower, has an appreciable slope (steeper than that of the névé), and may be confined between the rocky walls of an enormous trench (fig. 271).

Though flowing between "banks" like a river, a valley glacier has an enormously greater cross-section, being hundreds, or even thousands, of feet in depth, and also of great width. This large cross-section as compared with that of an equivalent river is a necessary accompaniment of a slower rate of flow.

The cross-profile of the surface of the névé is found to be concave, that of the glacier-tongue convex.

Glacier Ice.—The superficial layer of the névé is loose snow, but beneath the surface the material is more granular, and the amount of air entangled between the grains decreases downward. The deeper layers are compact ice, the large crystal-grains composing which are dovetailed together in optical contact, so that the lines of division between them are not apparent on a freshly broken surface as yet unaffected by melting. Such ice is clear and blue by transmitted light.

F. G. Radcliffe, photo.

FIG. 270.—The Tasman Glacier, New Zealand. To the left of the centre the Rudolph Glacier joins the Tasman, bringing with it a vast quantity of surface moraine, which joins with the lateral moraine of the Tasman Glacier to form a median moraine.

N.Z. Geological Survey, photo.

FIG. 271.—The Franz Josef Glacier, New Zealand.

Farther down the valley, in the ice-stream, the ice is compact, but layers of white ice (containing a little entangled air) generally alternate with the clear ice, so that the ice is stratified. The layers, at first parallel to the surface of the névé, become much distorted by the flow of the glacier A pseudo-stratification is produced also by shearing, where slabs of ice slip over one another owing to the deeper portion of the glacier being retarded by an obstacle.

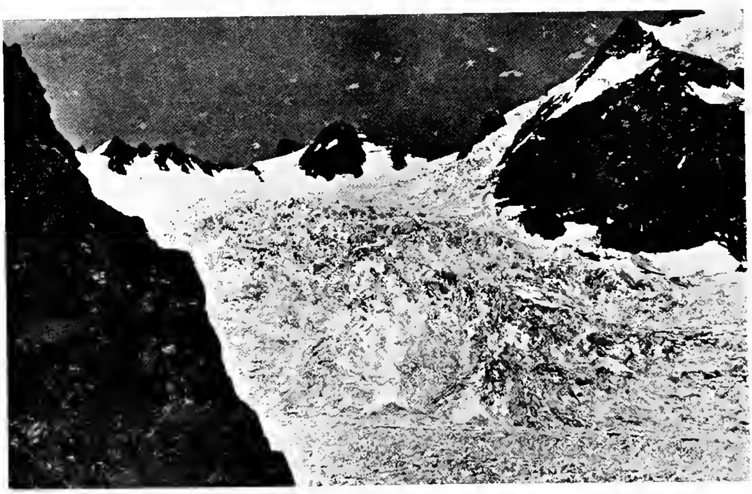
The Flow of Glaciers.—Ice-streams flow at rates varying from an inch or two to 60 ft. or more per day. The velocity depends on a number of factors, among which is the general slope of the land-surface; but the most important factor must be the volume of ice that has to be carried away, which will depend on the area of the gathering-ground and on the precipitation. The most rapidly flowing glaciers are those of Greenland and Antarctica, which act as outlets from the great inland ice sheets through gaps in the mountain-rims. In New Zealand the glaciers of the western slopes of the Southern Alps are said to flow much more rapidly than those of the eastern side, the average western slope being steeper, while the precipitation on the western side of the divide is much heavier than on the eastern side. Observations by the New Zealand Geological Survey seem to show, however, that the rate of flow of the Franz Josef Glacier is not so rapid as has been supposed. The Franz Josef (fig. 271) and Fox Glaciers —the two largest glaciers of the western slope—because of their rapid flow, combined with large volume, extend to within 700 ft. of sea-level, whereas on the eastern side the Tasman Glacier (figs. 267, 270), which is the largest and reaches to the lowest level, ends at a height of 2,354 ft. The rate of flow of the Tasman Glacier opposite the Malte Brun hut is 2 ft. per day in the centre, diminishing to a few inches per day at the sides.*

The fact that the rate of flow of a glacier is not the same throughout its width but is more rapid in the middle than at the sides shows that an ice-stream does not simply slide forward as a rigid body, but, though crystalline, really flows somewhat after

*A record of observations on the rate of flow made in the summer of 1913–14 by Captain B. Head is preserved in the visitors' book at the Malte Brun hut. The finding of one of Captain Head's pegs eight years later, after it had been carried approximately a mile down the glacier, has confirmed the general accuracy of his observations.

N.Z. Geological Survey, photo.

FIG. 272.—Crevasses forming in the névé of the Franz Josef Glacier, N.Z.



N.Z. Geological Survey, photo.

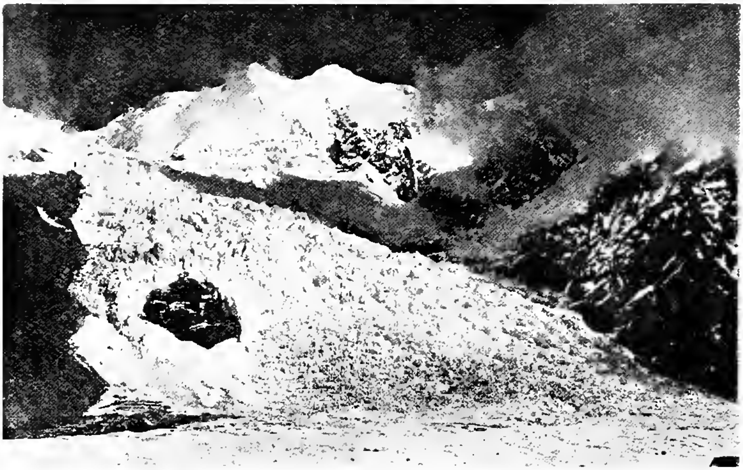
FIG. 273.—The great ice-fall of the Franz Josef Glacier, N.Z

the manner of a fluid, being retarded by friction close to the sides and bottom of its channel. Such flow of crystalline material, in which the molecules must maintain definite geometrical relations to neighbouring molecules in the same crystal, is essentially different from the flow of a non-crystalline substance like pitch, which is really only an extremely viscous liquid.

Rotation of ice-grains would allow the material to flow forward like a mass of shot, and it has been calculated that only a very small rotation of each grain would be required to produce the observed differential movement. The problem is not so simple as this statement would imply, however, for the grains cannot roll freely, being interlocked.

Glacier ice resembles crystalline rocks in texture, and flow of deep-seated crystalline rock is known to take place. It takes place only under great pressure, and is a matter of slow readjustment of the crystals of the minerals composing the rock by transfer of material from one part of a crystal to another and from one crystal to another by solution and redeposition. The flow of the granular ice of glaciers is probably analogous to this, though the pressures involved and the very important time factor are much smaller. Melting probably takes place where the greatest stresses occur, followed by refreezing in crystal continuity with pre-existing grains as the stresses are relieved, and this perhaps permits some rotation of the grains.

Crevasses.—It is gravity that causes a glacier to flow, and so the surface of the ice must have a general slope in the direction of flow. The slope is generally variable, however, changes in slope corresponding to inequalities of the rock floor. Stresses set up by the distortion of the ice where it passes over steep parts of the floor result in the formation of fissures, which are termed *crevasses* (fig. 272), and where the slope is very steep the multiplication of crevasses transforms the glacier into an *ice-fall* (figs. 273, 274). Crevasses are formed by other unevennesses in the channel, such as sharp bends, and some also, in large glaciers, are due to the more rapid flow in the middle of the stream. The deeper ice, being under pressure, and so acting more like a plastic substance, adjusts itself to the differential movement by flow, but that near the surface may be torn apart, leaving crevasses that extend to a depth of perhaps 200 ft. or 300 ft. Tension due to the more



F. G. Radcliffe, photo.

FIG. 274.—The ice-fall of the Hochstetter Glacier (a secondary glacier tributary to the Tasman Glacier), N.Z.

C. A. Cotton, photo.

FIG. 275.—Crevasses on the Tasman Glacier, N.Z., opposite the Malte Brun hut. The glacier flows from right to left. Near the middle the crevasses make angles of 45° with the sides, but near the sides they curve around and become transverse.

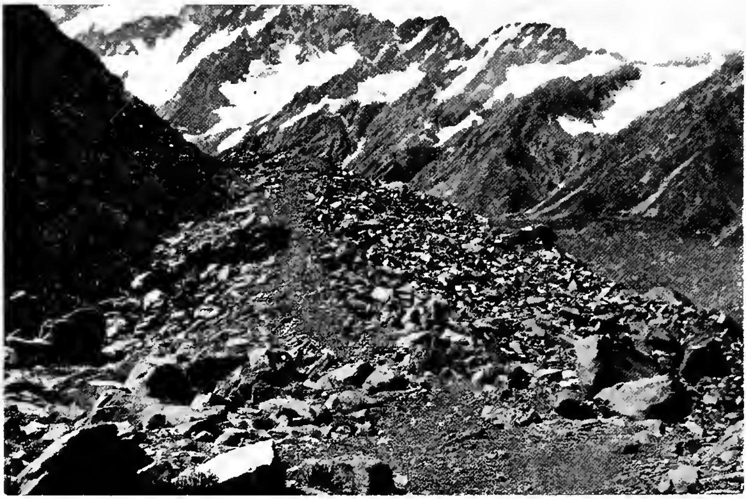
rapid movement of the middle portion of the glacier results in the formation of two sets of crevasses, one on each side of the middle line, pointing down-valley at angles of 45° with the sides (fig. 275). Crevasses when once formed may remain open for a long time, and they are twisted away from their original directions by the differential movement of the ice. Thus the crevasses due to tension, which point diagonally down-valley near the middle of the glacier, become more and more nearly transverse as the sides are approached, and close to the sides may even curve around still farther and point up-valley (fig. 275).

L. Cockayne, photo.

FIG. 276.—Seracs on the Franz Josef Glacier, N.Z.

When a glacier is broken into slices by numerous close-set crevasses its surface naturally becomes very uneven. The irregularities of the surface when modified into sharp ridges and pinnacles by melting are termed *seracs* (fig. 276).

Moraines.—Rock-fragments, large and small, broken by weathering from mountain peaks and slopes, fall on the surface of a glacier, and others are carried down by avalanches of snow and of névé ice from hanging glaciers and snowfields. This material, which accumulates in heaps on the ice, is termed *moraine*, and the



C. A. Cotton, photo.

FIG. 277.—Lateral moraine of the Hooker Glacier, Southern Alps, N.Z., stranded on the valley-side owing to shrinkage of the glacier.

R. Speight, photo.

FIG. 278.—Median moraine, Ramsay Glacier, Southern Alps, N.Z.

same name is given to all the rock-waste carried and eventually deposited by glacier ice. Various kinds of moraines are distinguished. *Surface moraines* are carried on the surface, but some waste originally on the surface falls, or is washed by streams of water, into crevasses, and some waste also is plucked or scraped from the bottom and sides of the channel. When dragged along under the ice it is *subglacial moraine*, and when carried in the body of the glacier, *englacial moraine*. The enormous quantity of morainic material that may be seen on the surface and embedded

C. A. Cotton, photo.

Fig. 279.—Moraine-covered surface and terminal face of the Hooker Glacier, Southern Alps, N.Z.

in the ice of glaciers testifies to their efficiency as transporting agents. That they are corrading agents also is shown by the large amount of finely-powdered rock (rock-flour) carried away by the rivers that flow from glaciers, which are given by it a characteristically "milky" appearance. This rock-flour must be produced by the abrading action of rock-fragments dragged along in the bottom layer of ice. So finely powdered is the rock-flour in the water of the rivers from the Tasman and Godley Glaciers

R. Speight, photo.

Fig. 280.—Terminal face of the Franz Josef Glacier, N.Z.

N.Z. Geological Survey, photo.

Fig. 281.—Waiho River emerging from a cave in the terminal face of the Franz Josef Glacier, N.Z.

that sufficient remains in suspension to make the water milky after it has passed through the settling-basins formed by the large lakes Pukaki and Tekapo.

Surface moraines at first form ridges, made up of coalescing heaps of fragments, along the sides, and are then termed *lateral moraines*; and where two glaciers join, their adjacent lateral moraines join also to form a ridge in the middle of the combined glacier, which is termed a *median moraine* (figs. 270, 278). There may be several median moraines, resulting from the junction of a number of secondary glaciers with a trunk glacier, so that the surface of the ice becomes covered practically from side to side. Towards the head of a glacier—in the region of "alimentation," where snow-fall and avalanches are adding to the volume of ice—surface moraines are being constantly buried, and very little moraine may be visible at the surface; but down the valley at lower levels—in the region of "ablation," where the surface ice is wasting away by melting and evaporation—the moraine is again exposed. The larger glaciers of the eastern side of the Southern Alps are so full of waste that for the last few miles of their courses they are completely covered by heaps of moraine (fig. 279).

Steep and rapidly flowing glaciers, such as the Fox and Franz Josef Glaciers, on the western side of the Southern Alps, are relatively free from surface moraines, partly because their rapid flow allows the waste to be carried in a thinner stream, but chiefly because the waste is swallowed up by the very numerous crevasses on the broken surface of the ice of such glaciers.*

Lower Limits of Glaciers.—As glaciers descend towards low levels they dwindle in cross-section as a result of ablation (loss by melting and evaporation). Streams of water are formed on the surface. These make their way eventually down crevasses and circular pits, termed *moulins*, originating in a manner somewhat analogous to the formation of sinkholes in limestone, and may unite to form a single trunk stream beneath the glacier. At the lower extremity, or *terminal face*, of the glacier there is generally a cliff of ice (figs. 279, 280), from a cave in which the subglacial stream emerges (fig. 281).

* In the case of the glaciers mentioned it is explained also that the rocks forming their valley-sides shed less waste than do the shattered, crumbling rocks of the eastern side of the Southern Alps; but this fact does not account for the almost complete absence of surface moraines.

In Greenland, Alaska, and Antarctica glaciers descend to the sea, and blocks breaking away from their cliffed margins form icebergs. In the temperate zones, on the other hand, the terminal faces of glaciers are commonly several thousand feet above sea-level. The Fox and Franz Josef Glaciers, mentioned above, are exceptional in descending so near to sea-level.

Ice Caps.—*Ice caps*, *ice sheets*, or, as they are sometimes termed, "continental glaciers," in glacial periods covered large areas in comparatively low latitudes, where there are now no permanent accumulations of snow and ice, but are now confined to polar regions, the largest being that which covers Antarctica, while another occupies the interior of Greenland. They attain a thickness of thousands of feet, and have a smooth surface, highest at the centre of accumulation and sloping very gently towards the margin. The ice spreads outward very slowly, so as to carry away the snow that falls. Crevasses evidencing such movement have been observed in Antarctica.

In Victoria Land, which lies south of New Zealand, the inland ice sheet of Antarctica is cut off from the sea by a range of mountains, and the ice flows through gaps in the mountains as enormous, rapidly-flowing valley glaciers. In some parts of Antarctica, however, the front of the ice sheet advances into the sea.

Piedmont Glaciers.—In high latitudes, and in glacial periods in lower latitudes, the ice of a valley glacier debouching on a plain may spread out as a flat cake, or that of several glaciers may coalesce to form what is termed a *piedmont glacier*, which, considered apart from the ice-streams that feed it, behaves somewhat like an ice sheet. In the last glacial period in New Zealand a piedmont glacier seems to have occupied the southern part of the basin of Lake Te Anau, being fed by glaciers from the Clinton Valley and the valleys now forming the arms, or "fiords," of the western side of the lake.

CHAPTER XXI.

GLACIATION.

Glacial erosion. The sculpture of mountains by glaciers. Sculpture above the general ice-level. Overdeepening. Hanging valleys. Glaciated valley profiles. Complex cross-profiles. Straightening of valleys.

Glacial Erosion.—Moving ice is an active corrading as well as transporting agent. Both valley glaciers and ice sheets erode, though the resulting land-forms are different in the two cases.

Though the ice sheets of Antarctica and Greenland and the glaciers now found in alpine valleys throw important light on the process of glacial erosion, it is in regions where glacial erosion no longer operates, or where the glaciers have now shrunk to insignificant proportions, that ice sculpture has produced its most important topographical effects. Such regions were subject to the action of ice for a restricted period, the oncoming of frigid conditions—a "climatic accident" (p. 213)—putting an end to one cycle of normal erosion, and the disappearance of the ice leaving a glacially sculptured surface on which normal agents have now begun to work in a new cycle.

In these regions the surfaces upon which glacial erosion began to work were, in general, normally eroded land-surfaces, with well-developed valley-systems in various stages of youth, maturity, and old age. In high and mountainous areas the ice flowed away as valley glaciers along the lines of pre-existing valleys, and the peaks and portions of the ridges and spurs stood out above the ice-level. Over the more nearly level surfaces, on the other hand, given sufficiently cold conditions and ample snowfall, thick ice sheets came into existence. Such ice sheets carved no very striking topographic forms, except locally where the movement of the ice was guided into certain channels by pre-existing topographic features, when troughs were ploughed out somewhat similar to those described below as produced by valley glaciers. Generally they merely smoothed and rounded prominences, removed all the waste-mantle from the rocks underlying the thicker parts of the ice sheet

Rose, photo.

FIG. 282.—Cirque at the head of the Clinton Valley, between Lake Te Anau and Milford Sound, N.Z. From McKinnon's Pass.

C. A. Cotton, photo.

FIG. 283.—Hanging cirque, or corrie, overlooking Lake Ada, Arthur Valley, Milford Sound, N.Z.

(sometimes thus excavating hollows, which are now lakes), and grooved, polished, and scratched the bare surfaces of the hard rocks by means of the rock-fragments they dragged along with them.

The Sculpture of Mountains by Glaciers. — The most striking effects that have been produced by glacial erosion are those found in mountainous areas that have been occupied by valley glaciers and snow- or névé-fields, the erosive action of which has produced features that contrast very strongly with those associated with normal erosion. The chief of these are as follows:—

(1.) The heads of valleys that have been occupied by glaciers are different in form from those shaped entirely by normal agencies. Glaciated valleys retain their width to their heads or even expand there to form great amphitheatre-like hollows, enclosed by almost vertical walls (fig. 282). Hollows on the sites of former hanging glaciers are also of similar form. These are the armchair-like niches so common in glaciated mountains, and belong, with the valley-head amphitheatres, to the class of forms generally termed *cirques* (fig. 283). Being very striking landscape features, they have received vernacular names in most of the European countries in which they occur. They are, for example, termed "cwms" in Wales, and "corries" in Scotland. Though the steep-walled heads of the larger glaciated valleys and the armchair-like "corries" appear to be of similar origin (Chapter XXII), the former may be conveniently referred to as *valley-head cirques*, while the latter may have the Scottish term *corrie* reserved for them, or may sometimes be termed *hanging cirques*.

(2.) The valleys are broad-floored and steep-sided (U-shaped) (figs. 284, 285). The curves in them are few in number and of wide radius. In longitudinal profile they are uneven, occasional steep descents (*steps*) being met with (fig. 292), which are separated by nearly level stretches, occasionally with reversed slopes that give rise to lakes.

(3.) Tributary valleys almost invariably join the main valleys with strongly discordant junctions — that is, as *hanging valleys* (fig. 286). The stream of water which now occupies a hanging tributary valley either plunges from its lip into the main valley as a waterfall or cascade, or has cut but a small notch in the lip in the post-glacial cycle (figs. 286, 290).

(4.) In addition to the small lakes which occur in the valleys, as described above, the lower parts of the large valleys are frequently

Muir and Moodie, photo.

FIG. 284.—U-shaped, glaciated valley of the Routeburn, Otago, N.Z.

Muir and Moodie, photo.

FIG. 285.—U-shaped, glaciated valley of the Pembroke River, entering Milford Sound, N.Z. The sound is here very deep, and so the valley here shown is hanging high above the floor of the main valley (the fiord, or "sound").

occupied, or furnish evidence of having been occupied since the retreat of the glaciers, by lakes of large size. Such lakes are generally impounded by dams of boulders and other waste which have been carried as moraines by glaciers, but they are very deep, and it is generally evident that, even if the morainic dams were absent, lakes, though of rather smaller size, would occupy their sites, and would be bounded at the down-valley ends by bed-rock—that is, would occupy basins apparently excavated in the rock of the valley-bottoms.

These features, which are constantly found in regions that have been occupied by glaciers, and which are strikingly unlike the forms produced by other sculpturing agencies, are confidently attributed to glacial erosion.

Sculpture above the General Ice-level. — In most regions of glaciated mountains there is a very striking contrast between the land-forms developed below the level of the surface of the main glaciers and névé-fields of the Glacial period and those developed above it. Below this level (which is, of course, not everywhere the same, but rises towards the centre of maximum snow-accumulation) wall-sided troughs and featureless glaciated slopes dominate the land-scape, but above it the forms are much more diversified, and the average mountain profiles are much less steep (fig. 293). Though the average slopes are relatively gentle, however, the surface is often extremely rugged, and precipices abound. The average upper slopes are a relic of the pre-glacial topography, but this may be modified very considerably by the development of cirques and by weathering of steep slopes above the level of the snow-accumulations in the cirques.

Overdeepening.—The trough-like, or U-shaped, transverse profiles of glaciated valleys and the presence of hanging tributary valleys point alike to the principal erosive activity of ice-streams confined in valleys, which has been termed *overdeepening* (Penck, 62). The glacier cuts vigorously downward, especially where it is thickest. This leads also to *oversteepening* of the sides of the valley (fig. 287).

Hanging Valleys. — Though the floors of the main glaciated valleys have been sunk by the overdeepening process far below the pre-glacial floors, and also far below the depth attained by the floors of tributary valleys, there is no reason to believe that at the height of the "ice-flood," as it has been called, when glaciers reached

C. A. Cotton, photo.

FIG. 286.—Hanging valley, tributary to the Eglinton Valley, near Te Anau, N.Z.

N.Z. Tourist Department, photo.

FIG. 287.—Glaciated trough with oversteepened sides, Clinton Valley, head of Lake Te Anau, N.Z. View from McKinnon's Pass, at the valley-head

their largest dimensions, secondary glaciers in general joined the trunk glaciers as ice-falls. It is probable, on the contrary, that the majority of glacier junctions were then accordant (fig. 288), as some are at the present day (fig. 289).

In an accordant junction, however, whether it be of ice-streams or water-streams, it is the surfaces of the streams that join at grade. There is a tendency both in glaciers and in rivers to adjust the size of every cross-section of the channel to suit the volume of ice or water that must pass through it. (This *law of adjustment of cross-sections* is due to Penck, 67). The cross-section of a glacier is,

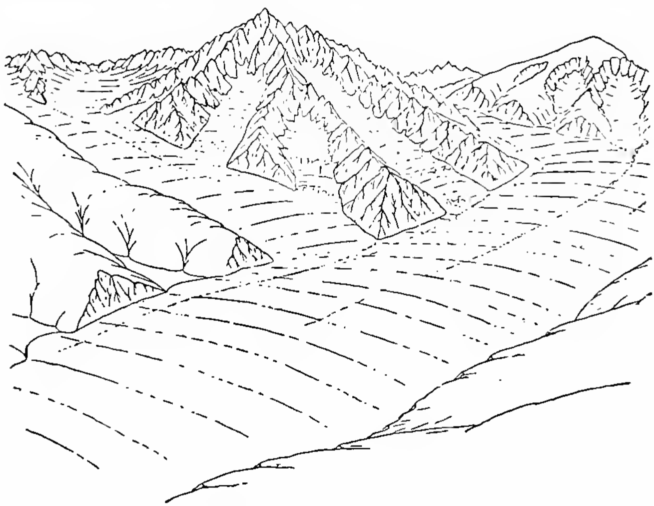


FIG. 288.—Diagram of valley glaciers with accordant junctions. (After Davis.)

of course, enormously greater than that of an equivalent river, and the whole trough or glaciated valley, in so far as it is occupied by the glacier, is analogous with the actual water-channel in a river-valley. The glacier tributary has a smaller cross-section, and is thus shallower, than the main, and so the floor of the tributary valley must be at a higher level than that of the main, so that it forms a hanging valley when no longer occupied by the ice (fig. 290). The same is true of the channel of a tributary river the surface of which joins that of its main accordantly, and if the rivers were diverted so as to leave the channels empty a hanging junction of the floors would be seen, though on a much smaller scale than in

the case of glacier channels, on account of the much smaller cross-sections of the streams.

Not all hanging valleys in which the discordance is due to glacial overdeepening are themselves glaciated. Near the margins of glaciated areas, and in districts that have been only slightly glaciated, some of the side valleys tributary to the glacier-troughs have themselves escaped glaciation. Such valleys are left hanging owing to overdeepening of the main valleys by the ice. They have the transverse profiles of normal stream-eroded valleys

C. A. Cotton, photo.

FIG. 289.—Accordant junction of the Ball Glacier with the Tasman (foreground), Southern Alps, N.Z.

(fig. 315). Some non-glaciated hanging valleys occur on the sides of the glaciated trough occupied by Lake Wakatipu, N.Z.

Glaciated Valley Profiles.—The law of adjustment of cross-sections explains also many of the steps which occur in the longitudinal profiles of glaciated valleys.

Where a valley glacier expands at the head into a wide sheet of névé—*i.e.*, is fed by the snow accumulating in a wide, composite cirque, or group of converging cirques—the ice-stream flowing away through the narrower valley below demands a deeper channel (unless its size is much reduced by ablation). When such a channel has been excavated, the glacier-trough, as seen after the disappearance

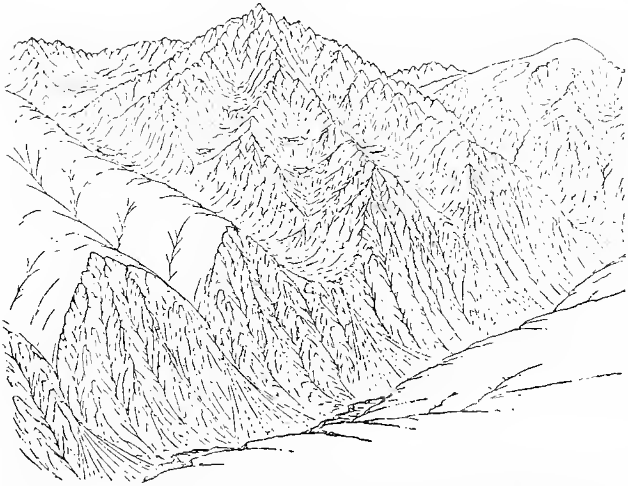


FIG. 290.—An area formerly occupied by valley glaciers (as in fig. 288), after the disappearance of the ice, showing hanging valleys. (After Davis.)

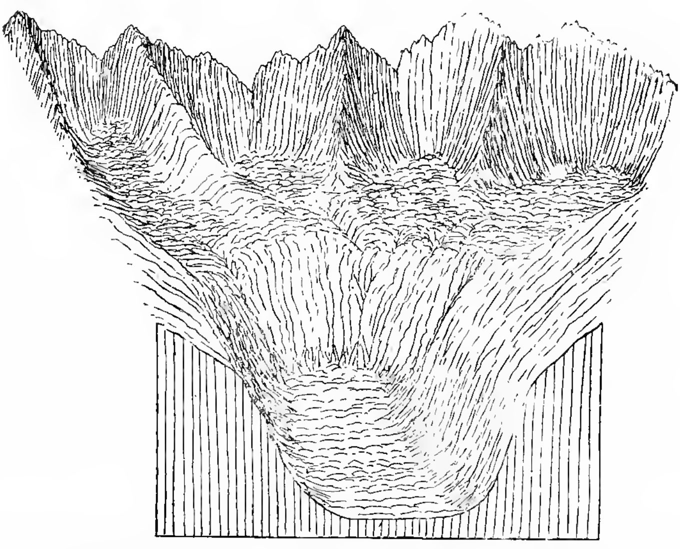


FIG. 291.—Diagram of a step, or "trough's end," at the head of a glacial trough that has been fed from a group of converging cirques

of the ice, ends headward in a step—the "trough's end," a feature found in many of the valleys of the European Alps—below the level of the feeding cirques (fig. 291). The trough's end was not, in such cases, the head of the glacier, but merely a step in the glacial-valley profile (Davis, 5, p. 422). In New Zealand the form of the pre-glacial surface seems to have been generally unfavourable to the formation of groups of converging cirques and of glaciers with expanded heads, and such troughs' ends are not commonly found.

Where the volume of a glacier is increased by the incoming of a tributary an expansion of the cross-section of the channel is required, and generally a step results (fig. 292).

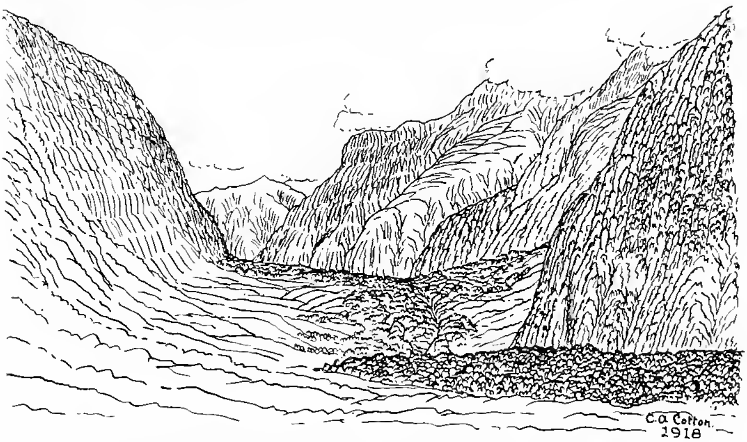


Fig. 292.—A step in the Arthur Valley, near Milford Sound, N.Z., just above the point where the Sutherland Falls enter the valley. At this point a tributary glacier joined the ancient Arthur Glacier.

Other steps, however, are directly traceable to differences of rock in the valley-floors, some rocks—particularly shattered rocks—being much more easily eroded by ice than others. These steps belong to the "young" stage of glacial-valley erosion. They retreat up-valley, and prolonged glacial erosion would eliminate them, producing a "mature," or "graded," glacial valley.

Associated with such steps—immediately above them—low transverse ridges of rock, which were overridden by the glaciers, occur in the valleys of the Alps, and convert the treads of the steps into basins. These barriers are termed *verrous* or *Riegel*. They are not conspicuous features of the glaciated valleys of New Zealand, owing, apparently, to the absence of transverse outcrops of

sufficiently resistant rock. They have been observed, however, in Antarctica (G. Taylor).

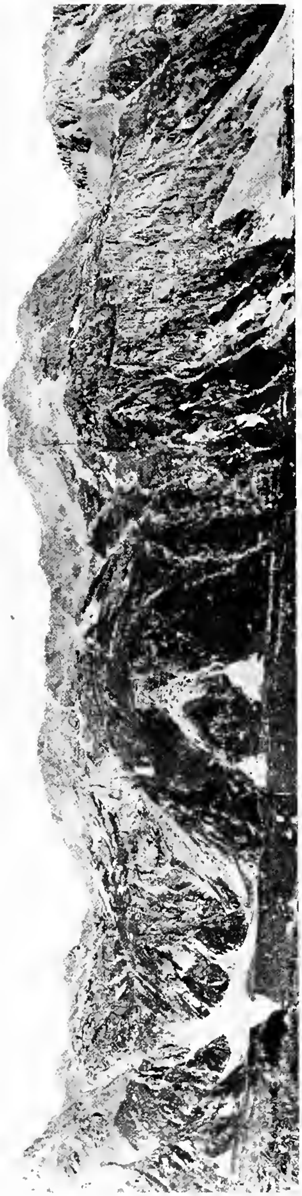
Complex Cross-profiles.—The tranverse profile of a glaciated valley is not always simply U-shaped, but is often made up of two distinct elements, giving a U-in-U appearance—a steep-sided inner U within a flatter, widely-opened U, or catenary curve, the steep inner slopes meeting the gentler outer slopes at a distinct angle. The bench above the angle, which has the appearance of a remnant of a valley existing before the iuner trough was cut, is termed a *shoulder*. In some valleys of the European Alps several shoulders occur, one above another.

Shoulders are common in the glaciated districts of the South Island of New Zealand (fig. 293). Even in the Fiord district of western Otago, where the rock is resistant gneiss with few joints, and the average slopes are very steep, approaching 70°, distinct shoulders may be seen at some places on the sides of the glaciated troughs (Andrews, 23). Several shoulders one above another on the side of Milford Sound are seen in fig. 432.

A single satisfactory explanation of this benched profile so commonly present in glaciated valleys has not yet been given, and it is probable that shoulders result from various causes. The complex cross-profile does not seem at all analogous to the "valley-in-valley" form in normally eroded river-valleys, for the glacier-bed as a whole is not analogous to a river-valley, the whole of the former being covered by the ice-stream, but only a narrow ribbon of the latter by the water-stream. Moreover, the downward limit of glacial erosion is not closely governed by base-level, as is that of river erosion.

To ascribe the excavation of the inner trough to overdeepening due to the thicker, heavier, and more rapidly flowing middle portion ot the glacier would leave unexplained the sharpness of the angle between the shoulders and the slopes of the inner trough.

Shoulders have been regarded as remnants of the pre-glacial valleys (Penck; Davis), and from this point of view the inner trough only was the real channel of the glacier, and such marks of the presence of the ice as are found on the shoulders might then be ascribed to temporary overflow of the "banks," not enduring long enough to modify appreciably the pre-glacial topography. Evidence of glacial erosion on the shoulders does not necessarily imply that a great thickness of rock has been removed from them, or that their from has been much modified. As



C. A. Cotton, photo.

FIG. 293.—Shoulder bordering the inner trough of the Hooker Valley. View looking across the Hooker Glacier, N.Z., from the Hooker hut.

pointed out previously (p. 291), there is a strong contrast between the slope of the oversteepened trough-wall and the average slope above the general ice-level. This type of shoulder is illustrated in fig. 293, a view across the shrunken Hooker Glacier, in the Southern Alps, New Zealand.

Another explanation of glaciated shoulders ascribes the inner, U-shaped glacier-troughs to an epoch of glaciation later and characterized by smaller glaciers than that in which the wider valleys at the shoulder level were cut and the glaciers reached their maximum size (Richter, 71). This suggestion, which differs from the foregoing in that it ascribes to glacial erosion a larger share in the shaping of the cross-profile of the outer valley, may afford a correct explanation of some shoulders, for there is incontestable geological evidence that in Europe several great fluctuations in the size of glaciers took place during the "Glacial period," epochs of intense glaciation being separated by epochs of relatively mild climate—perhaps as mild as, or milder than, that of the present day. Such a succession of glacial epochs, though probable, has not yet been proved to have occurred in New Zealand.

De Martonne (61) also ascribes to glacial erosion the shaping of the successive valley-floors remnants of which form the shoulders in Alpine valleys, but allows for very little

glacial overdeepening, and assumes that the chief work of the glaciers has been to widen young river-valleys cut as a response to uplift of the Alps immediately before the Glacial period and in the interglacial epochs of mild climate.

If, as seems probable, the inner glacial trough is more often due to glacial overdeepening, the sharpness of the separation of the inner trough from the shoulder appears to emphasize the importance of the time factor. The duration of the period, or periods, of wide overflow must have been short as compared with the time during which the somewhat shrunken glacier has been engaged in overdeepening the inner trough. This is made evident by the manner in which the inner trough becomes prominent as existing glaciers—*e.g.*, those of the Tasman system in New Zealand—are approached. In the lower Tasman valley (formerly occupied as

C. A. Cotton, photo.

FIG. 294.—View across the Tasman Valley, N.Z., from the Hermitage. showing a hanging valley and a glaciated shoulder on the side of the main valley.

far as the foot of Lake Pukaki by a glacier of enormous size) no inner trough is seen, but farther up the valley it appears, bordered at first by shoulders (fig. 294). Still farther up, where the Tasman Glacier still exists, the trough form becomes dominant and in some places the shoulders are entirely cut away.*

* Much of the surface that was overridden by the ancient extended Tasman Glacier may be little modified by glacial erosion, but may owe its smoothness rather to its being part of the stripped fossil erosion surface (peneplain and plain of marine erosion) referred to in Chapter XI. The presence of numerous remnants of covering strata recently described by Speight (*Trans. N.Z. Inst.*, vol. 53, pp. 37–46, 1921) shows that part of this surface was overridden and only slightly modified in form by the former extension of the neighbouring Godley Glacier, at Lake Tekapo. It is not clear whether the glacier is the agent chiefly responsible for the removal of the weak cover, or whether the surface had already been stripped nearly bare by normal erosion before the advent of the ice.

A further cause of complex cross-profiles in glaciated valleys has been indicated by Penck (18 ; 68), who recognizes in the European Alps not only "terraces of rock which indicate older valley-floors" upraised by very late earth-movement, but also benches which he ascribes to the joining-together of the floors of adjacent corries. "At those places there is a regular succession of forms: the U-shaped bed of the main glacier, the steep slopes, and above those slopes a shoulder on which were lying the lateral affluents." It is clear that shoulders of the latter kind will be found only in those parts of glaciated districts, generally the axes of mountain-masses, where glaciation has been most intense and the pre-glacial forms have been destroyed, while those of the former kind may be looked for far down the valleys, where the ancient glaciers were dwindling.

Straightening of Valleys.—As glaciers deepen the valleys that they occupy they at the same time eliminate the smaller and smooth the larger curves by cutting off the ends of spurs. In some cases, where glaciers had insufficient time to modify their valleys to the form best suited to accommodate them, spurs may be seen partly truncated, the base of a spur surviving

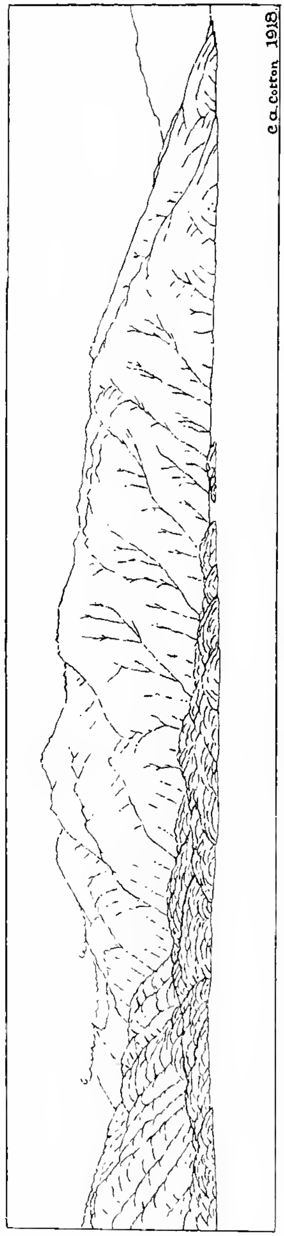


FIG. 295.—Basal remnants of a great spur truncated by glacial erosion, entrance to South Fiord, Lake Te Anau, New Zealand. The tapering spurs to the north (right) have escaped truncation, and preserve their pre-glacial forms.

as a concourse of irregular rocky hummocks (Davis, 4, p. 638). A large-scale example of incomplete truncation of a spur may be seen on the western side of Lake Te Anau, New Zealand, near the southern end. Great glaciers, descending from the mountains between the lake and the western coast, formerly occupied the valleys that are now arms of the lake. The glacier debouching from the arm known as South Fiord overrode the spur on its southern side, reducing it to the hummocky topography seen in fig. 295. Numerous examples of incompletely truncated spurs at Lake Manapouri and in the Canterbury valleys of the Southern Alps have been described by Speight (73; 77) (fig. 296).

R. Speight, photo.

Fig. 296.—Partially truncated spur, showing a basal remnant, Waimakariri Valley, Canterbury, N.Z.

Truncated spurs are characteristic of glaciated valleys. They are generally remnants of pre-glacial spurs, but even above the point of truncation the pre-glacial form may be entirely destroyed by deep erosion accompanying glaciation (fig. 306). The spur-ends (fig. 306) forming the side of a glacial trough show some resemblance to the facets of a fault-scarp, but are distinguished from them readily, as they are present on both sides of the valley, and are associated with other signs of glacial erosion.

CHAPTER XXII.

GLACIATION (*continued*).

Ice-stream erosion. Scouring and plucking. Cirques. Glacial sapping. Corries. Glaciated summit forms in regions of coarse- and fine-textured dissection. The cycle of glacial erosion.

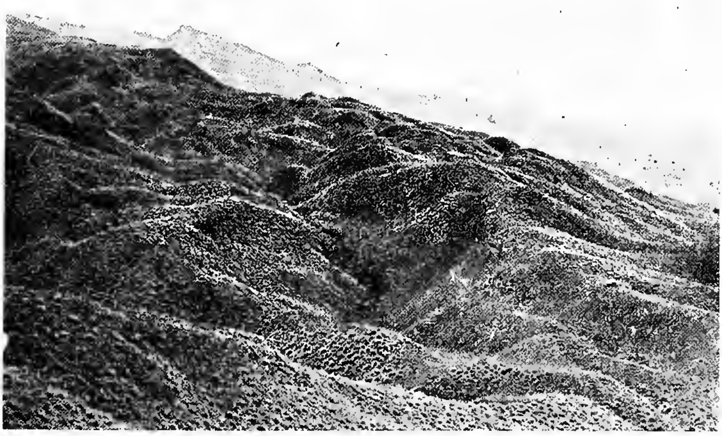
Ice-stream Erosion.—The characteristic sculpture of glaciated mountains is the work of a complex of processes, among which normal weathering (principally rock-breaking by physical agencies) plays an important part. Those parts of the surface that are permanently covered by snow or ice are protected, however, from weathering. Where such a covering is stagnant it is entirely proteetive, but where in motion it erodes, being responsible for the "ice-plough" action manifest in overdeepened valleys* and for the polished and mamillated or hummocky surfaces characteristic of areas that have been covered by widely spreading glaciers.

In New Zealand such "glaciated" surfaces are common on the less steep slopes that were covered by the ice of glaciers emerging from the alpine valleys of South Canterbury, and also in the Queenstown district, Otago (figs. 297–299). In both these areas the rocks presented rather low resistance to glacial erosion, consisting of shattered greywacke in South Canterbury and of mica schist in the Queenstown district. The ice markings left on the slopes of these districts take the form of irregular benches or terraces parallel in a general way to the direction of movement of the ice. Generally the benches are short and ripple-like, giving at a distance the impression of gigantic sheep-tracks, though a close examination reveals a highly irregular surface of whale-backed mounds alternating with rock-rimmed hollows, in some of which

* Some part of the deepening of troughs should perhaps be ascribed to the work of subglacial streams of water, derived from melting of the glacier ice, flowing under pressure and carrying much waste.

Muir and Moodie, photo.

FIG. 297.—Mamillated, or "glaciated," surface, Ben Lomond, Queenstown, N.Z. In the foreground is the present outlet of Lake Wakatipu (Kawarau Falls).



J. Park, photo.

FIG. 298.—Details of mamillated glaciated surface, Coronet Range. Otago, N.Z.

are tarns.* The hollows appear to mark weaker, more easily excavated parts of the rock. In other cases the benches run continuously for longer distances, though not quite horizontally and not strictly parallel to one another (fig. 299).

Near Lake Luna "these ice-cut terraces . . . vary from 30 ft. to nearly 70 ft. in height, and from a few yards to over two

J. Park, photo.

FIG. 299.—Ice-terraced slopes, Lake Luna, Queenstown district, N.Z.

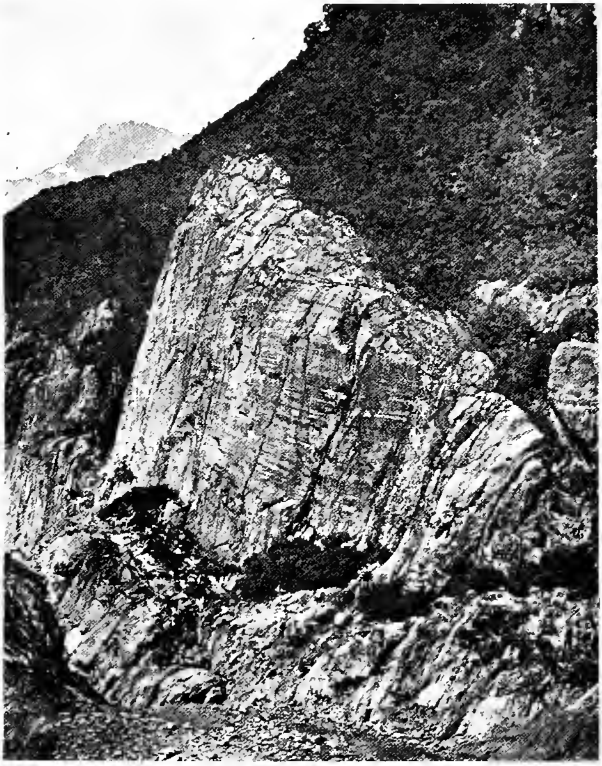
chains in width. They are excavated in a fairly hard quartzose mica schist. The broader benches often have an undrained depression at the back, generally close under the slope ascending to the next platform" (Park).†

* The term *tarn* is applied to the innumerable water-bodies too small to be called lakes that are found occupying hollows of various kinds in glaciated districts.

† 64, No. 7, p. 19, 1909.

On steep slopes, such as the sides of overdeepened troughs, glacial markings on relatively weak rocks are quickly obliterated by normal weathering.

The harder rocks of the Fiord district, western Otago, and of southern Westland are also grooved (fig. 300) and mamillated



R. Speight, photo.

Fig. 300.—The rock of a valley-side smoothed and fluted by glacial scour, valley of the Fox Glacier, Westland, N.Z.

(fig. 282, foreground) by the passage of the ice over them, but here very steep (glacially oversteepened) slopes predominate (fig. 287), and, though the mamillated pattern may often still be traced on these, it is less conspicuous than on gentle slopes, and distinct terracing does not occur.

N.Z. Geological Survey, photo.

Fig. 301.—Ice-scoured surface of granite, Boulder Lake, northern Nelson, N.Z.

R. Speight, photo.

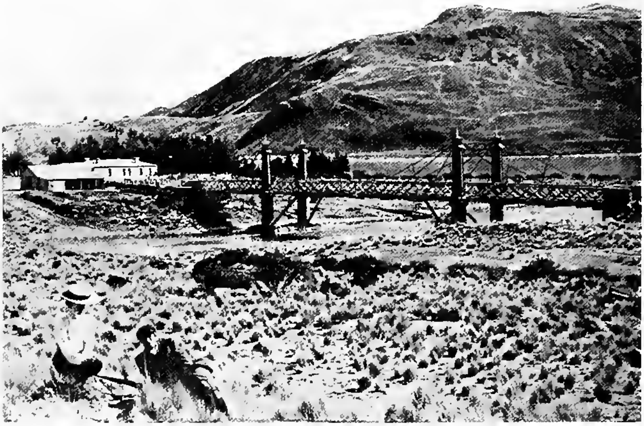
Fig. 302.—A *roche moutonnée* in the Waimakariri Valley, Canterbury, N.Z.

Glacial sculpture such as that just described does not itself indicate deep erosion, but frequently where it occurs, even on gentle slopes, the destruction of the pre-glacial normal topography shows that a considerable thickness of rock has been removed.

Scouring and Plucking.—The erosive work of moving ice is accomplished by *scouring* and *plucking*, and both these processes, no doubt, took part in producing the mamillated surfaces described above. *Scouring* is the work of rock-waste dragged along under the ice. Ice alone, though capable of removing loosened waste, is too soft to abrade compact rock. The ice of glaciers, however, being armed with fragments of rock, acts as a rasp. Its effectiveness as a powerful grinding agent is shown by the terraced and mamillated surfaces it leaves behind it. Where the "glaciated" surfaces of the rock hummocks of such a scoured region are well preserved, as they sometimes are in the case of very hard rocks, or, even in the case of softer rocks, if protected by a layer of fine waste, they are found to be not only roughly rounded but also smoothed and polished, though grooved and scored as well by the angles of the last rough fragments that were dragged across them (fig. 301). The direction of the striations shows the direction of movement of the ice.

Scouring goes on beneath the glaciers of the present day, shrunken and weak though they are as compared with those of the Glacial period, as is proved by the rock-flour (p. 283) that they yield on melting at the terminal face, and by the rounding of the edges and scoring of the surfaces of pebbles and boulders that have been transported as subglacial moraine (p. 317).

By *plucking* blocks of rock are removed from the floor and sides of a glacial channel. As a result of long-continued heavy pressure the ice grips the rock, partly by freezing to it and partly by friction, separation takes place at a joint or some plane of weakness, and a block is dragged away. This takes place generally on the down-stream side of some projection that is in course of removal—a mass of relatively resistant rock or the remnant of a partially truncated spur. Such projections are scoured smooth on the up-stream side ("scour side"), and are termed *roches moutonnées*, from a fancied resemblance of their mamillated forms to gigantic sheep (fig. 302). The down-stream side ("pluck side"), on the other hand, presents a ragged, quarried appearance (fig. 303).



Rose, photo.

FIG. 303.—A hill at Lake Tekapo, N.Z., that was overridden by the ice of the Godley Glacier, the direction of glacial flow being from right to left. The side of the hill (above the bridge) shows terraces due to glacial scouring, and the steep face on the left is the result of plucking.

Rose, photo.

FIG. 304.—McKinnon's Pass, between the Clinton and Roaring Creek cirques, Fiord district, N.Z. Direction of ice-movement, right to left. Plucked surface in foreground; scoured surface above and in middle distance. In the background is Mount Balloon.

Plucking takes place also where ice overflows through a gap in the wall of a cirque or corrie (fig. 304).

Cirques.—The formation of cirques (p. 289) is clearly the result of a combination of the downward erosive action of forward-moving ice with another phase of glacial erosion whereby the steep enclosing walls are formed and are caused to retreat, thus enlarging the area of the cirque. The former action is evidenced by the scraped and polished, mamillated bed-rock floors of the cirques, sometimes hollowed out to such an extent that reversed slopes occur and the disappearing ice leaves hollows that become lakes or tarns. The other phase of cirque-formation is clearly active at the base of the surrounding cliffs, for the rugged walls can be satisfactorily accounted for by slumping and normal weathering if an active gnawing-away of the cliffs at their base has taken place. The undercutting which has thus caused the cirque-walls to retreat is well termed *sapping.*

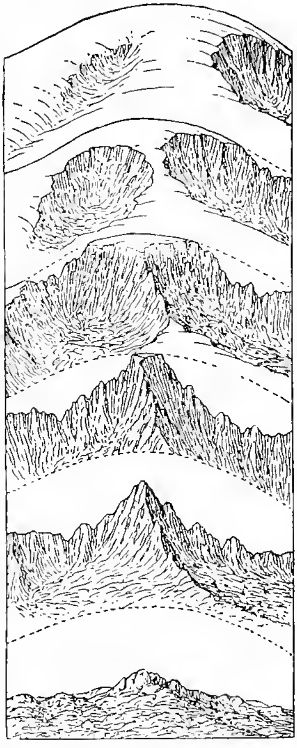
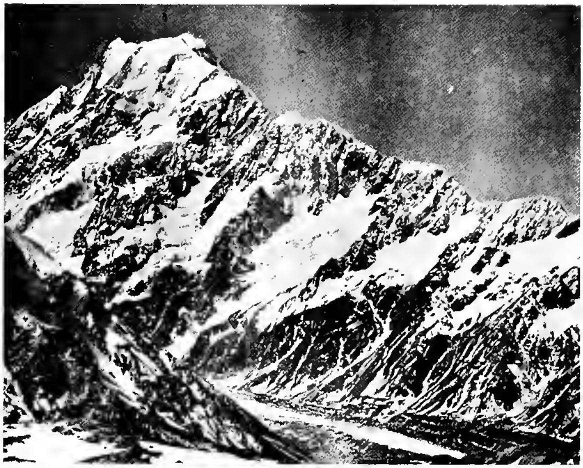


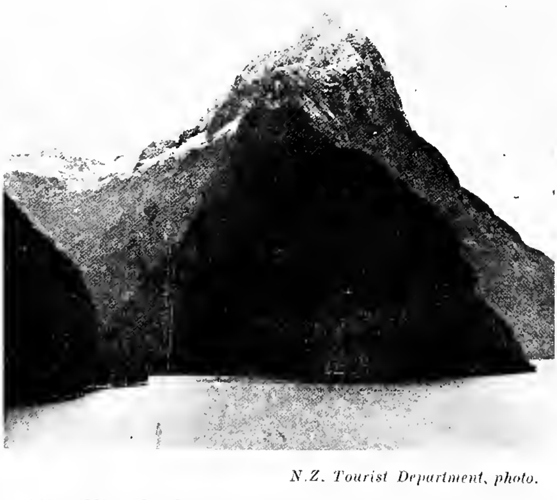
Fig. 305.—Successive stages in the symmetrical development of cirques in a domed mountain. (After Davis.)

Owing to the enlargement of neighbouring cirques by sapping, the residual portions of the mountain-tops between them are frequently much reduced (fig. 305). It is as though the mountains had been splashed with some mysterious rock-devouring acid. The steep walls of adjacent cirques may meet in a ragged *comb-ridge* (Hobbs), or *arête* (fig. 306). In other cases a high peak of pyramidal form remains, with its steep sides formed by the intersecting walls of three or more cirques, as in the case of the Matterhorn, in Switzerland. Numerous peaks of similar form, sometimes termed "horns," have originated in this way, or one side of the pyramid may be the oversteepened side of a great glacier-trough. In New Zealand, Mitre Peak, Milford Sound (fig. 307) is a good example.



F. G. Radcliffe, photo.

Fig. 306.—Mount Cook, N.Z., as seen across the Hooker Valley, showing corries separated by arêtes, spurs truncated by the Hooker Glacier, and stranded lateral moraines.



N.Z. Tourist Department, photo.

Fig. 307.—Mitre Peak, Milford Sound, N.Z. To the left (south) is an enormous cirque known as Sinbad Valley.

Mount Cook has been sharpened to a somewhat similar pyramidal form by the development of a larger number of small cirques (corries) (fig. 306). It is probably the remnant of a pre-glacial peak maturely dissected by glacial erosion (compare with fig. 305).

Muir and Moodie, photo.

Fig. 308.—A col, or gap, in the divide between the Routeburn and Hollyford Valleys, Otago, N.Z., resulting from sapping of the wall of a large corrie (shown in the illustration), the floor of which hangs high above that of the Routeburn Valley.

Cols (gaps in a ridge) also result from the intersection of the walls of opposing cirques, or of the wall of a cirque with that of a glacier-trough (fig. 308). Many mountain-passes have originated in this way. Frequently ice overflows through the gap from one cirque

C. A. Cotton, photo.

FIG. 309.—Cirque-wall at the head of Nurse Creek, Lake Te Anau, N.Z., the result of sapping.

F. G. Radcliffe, photo.

FIG. 310.—Tarn in a corrie overlooking the valley of the Hooker Glacier, Southern Alps, N.Z.

to the cirque or valley beyond, and the col is thus enlarged, lowered, and smoothed in outline to a U shape. In New Zealand, McKinnon's Pass, between Lake Te Anau and Milford Sound. originated in this way (fig. 304.) Ice from the cirque at the head of the Clinton Valley (fig. 282) overflowed through the col to the Arthur Valley. A similar col, the Lake Harris Saddle, forms a pass between the Routeburn Valley (draining to Lake Wakatipu) and the Hollyford Valley (draining to the west coast).

Glacial Sapping.—The most satisfactory hypothesis to account for the sapping of cirque-walls ascribes it to normal frost-action—freezing and thawing of water in crevices of the rock—at the bottom of the bergschrund, a curving crevasse which is open in summer around the margin of the snow- or névé-field (where cirques are still filled by such), separating it from the rock walls. It is known from observation (W. D. Johnson, 53) that, though at the top both walls of the bergschrund are composed of snow, at the bottom (in the case observed, at a depth of 150 ft.) one wall is ice, the other rock. The rock wall, moreover, was found to be wet, which indicates that thawing takes place during the day, for freezing will certainly occur every night in such a place. Frost-action must, therefore, be actively rending the rock. Rock-fragments of various sizes, recently quarried, formed the floor of the rift, and others were found embedded in the opposite (ice) wall, as though in process of removal by the glacier.

Whether the above be the correct explanation of the mechanism of the process or not, sapping is a fact of which there is ample evidence in the presence of the precipitous walls, in some cases thousands of feet in height, surrounding the numerous cirques found in glaciated mountains (fig. 309).

Since the disappearance of the ice from the majority of cirques, though sapping has ceased, crumbling of the oversteep walls has continued under the action of normal weathering and stream erosion, and all cirques are to some extent encumbered by talus slopes and alluvial cones. The form of many cirques remains remarkably fresh, however, the work of grading in the normal cycle following glaciation being scarcely begun.

Corries.—Hanging cirques, or corries, sometimes have floors so concave that they hold lakes or tarns (fig. 310). In less extreme cases, where there is not actually a backward slope on any part

of the bed-rock floor, it is at least so nearly horizontal as to present a striking contrast with the neighbouring slopes. It is this that gives the corrie its characteristic armchair-like form.

The shape of the floor does not seem to be governed by the sapping process. Cirque-floors are strongly scoured and overdeepened by the outflowing ice. Such overdeepening takes place chiefly where glacier-ice is thickest, and if the corrie-glacier dwindles

C. A. Cotton, photo.

FIG. 311.—Sutherland Falls, near Milford Sound, New Zealand.

owing to ablation towards the front of the cirque, and thins out to a terminal face there, it cannot erode the cirque-floor at the front, and so the differential deepening farther back may be understood.

Some corries hang above non-glaciated slopes, where apparently only hanging glaciers existed even at the height of the Glacial period. Others, hanging above the slopes of glaciated valleys, were perhaps hollowed out to the armchair form during the period of glacial

retreat, when the glaciers occupying them had shrunk to small dimensions, or during a later period of minor glaciation following that of maximum glaciation. The corries shown in figs. 283 and 308 are in the strongly glaciated district of south-western Otago. In that district corries are fairly abundant. From the lip of a large one, containing on its floor a lake, the Sutherland Falls drop 1,904 ft. to the floor of the Arthur Valley (fig. 311).

Glaciated Summit Forms in Regions of Coarse- and Fine-textured Dissection.—In regions of coarse-textured dissection the widely spaced valley-heads of the pre-glacial topography accommodated large snowfields, which etched out large cirques of perfect form, such as that of Sinbad Valley, Milford Sound (fig. 307). In

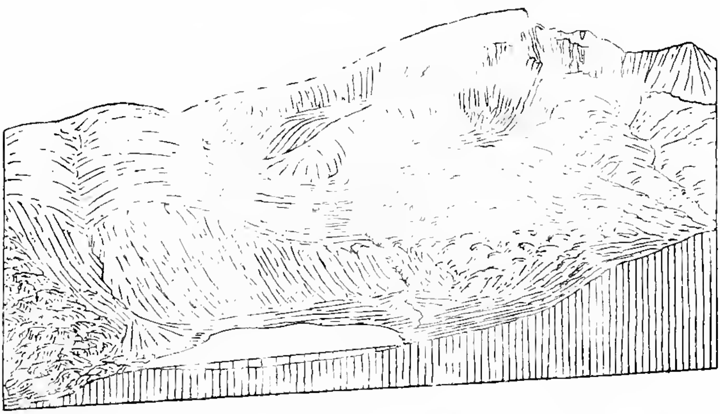


FIG. 312.—Diagram of Snowdon, North Wales. (After Davis.)

parts of the Fiord district mature glacial dissection of this coarse-textured type is found, giving rise to forms such as Mitre Peak (fig. 307) and Mount Balloon (fig. 304). On the borders of these areas, however, glacial dissection is less advanced, and even-crested ridges and relatively gentle upper slopes between the glacial troughs suggest the existence in pre-glacial times of a submaturely dissected plateau (23, p. 192).*

In other parts of the world cases are known where subdued, domed mountains in districts of coarse-textured dissection are immaturely dissected by glacial cirques, so that the glacial topography

* Probably (from analogy with the block-faulted district farther east) this was a dislocated plateau, with blocks standing at various levels.

is in strong contrast with the remnants of pre-glacial forms. Such contrasts, of the type illustrated in fig. 312 (see also fig. 305, upper part), are found in the mountains of North Wales, in the Rocky Mountains of Colorado, and in the Californian Sierras.

In districts where the relief due to pre-glacial erosion was fine-textured the contrast between the non-glaciated summits and the glaciated summit topography is less striking. Such is the case in the glaciated parts of the Southern Alps in Canterbury. There snowfields accumulating in the pre-glacial ravines became névés and glaciers; these sapped back to form numerous corries of somewhat irregular form which sharpen the mountain-crests (fig. 306).

The Cycle of Glacial Erosion.—Since glacial erosion involves the removal of a vast quantity of waste, it leads, like normal erosion, to a general lowering of the land-surface. It appears that sapping, together with the work of valley glaciers, would result eventually in destroying the relief of glaciated mountains. Glacially planed surfaces analogous to the peneplains produced by normal erosion are not known, however, for the glacial cycle has always been cut short at some stage earlier than that of old age by amelioration of the climate. Even the mountains of Antarctica, among which enormous glaciers remain at work, still retain strong relief, indicating that ice-action has not been at work long enough there to destroy the relief.

As in the case of normal sculpture, complete or almost complete destruction of the initial (in this case pre-glacial) forms marks the passage from young to mature dissection.

Near the margin of a glaciated area the summits retain their pre-glacial forms (developed by normal erosion), while towards the centre of glaciation—the heart of the mountain-range—these are more and more encroached on by forms due to high-level glaciation, until often, as in the central ranges of the Southern Alps, the latter alone are to be seen. Glacial erosion is then mature, whereas when normal pre glacial forms still occupy an appreciable part of the surface glacial erosion is still young.

Glaciated troughs also may be termed mature when "graded" —*i.e.*, when fit to accommodate glaciers with smoothly sloping surfaces, free from ice-falls. The floors of graded troughs do not necessarily have smooth, even slopes, however. They may retain steps corresponding to sudden expansions of the ice-streams where they receive tributaries.

CHAPTER XXIII.

GLACIATION (*continued*).

Glacial deposits. Stranded moraines. Erratics. Glacial drift. Glacial lakes. Ice-dammed lakes. The post-glacial cycle. Aggradation in the glacial period. Changes in drainage due to glaciation.

Glacial Deposits.—Ice-streams, like water-streams, may become overloaded. When the ice of a glacier or ice-sheet has moved far outward from the centre of accumulation it has picked up so much waste that it loses its erosive activity, and, as the thickness of the ice dwindles owing to melting, it begins to deposit its load. When, finally, owing to climatic change increasing the rate of melting, the ice-front rapidly retreats, the whole of the remaining load is dropped. Many large boulders, as well as vast quantities of finer material, remain scattered over large areas, and help to prove the former great extension of the ice. Boulders left standing conspicuously on slopes and hilltops are termed *perched blocks* (fig. 313).

Some of the boulders and pebbles of hard rocks which have been dragged along under the ice show evidence of considerable wear, having the angles rounded, while the sides are worn more or less flat and are polished and striated (fig. 314). The striae sometimes run in various directions, showing that the boulder was twisted about as it was dragged along. Such boulders and pebbles are the tools with the aid of which the ice did its erosive work.

Stranded Moraines.—Some of the morainic material delivered by a glacier at its terminal face is carried away by the streams formed by the melting of the ice, but some of the coarse waste is dropped in heaps, forming *terminal moraines.* Rapid shrinkage of one of the heavily waste-covered glaciers east of the main divide of the Southern Alps would probably leave stranded a belt of its surface moraine as a terminal moraine.

C. A. Cotton, photo

FIG. 313.—Perched block near Arrowtown, Otago, N.Z. The weight of this block, as estimated by Park, is 230 tons.

C. A. Cotton, photo.

FIG. 314.—Part of the polished and scored under-surface of the boulder shown in fig. 313.

Glaciers are subject to short-period fluctuation in length owing to variation in the snowfall at their heads. Thus a glacier may deposit moraine as it retreats for a few years and later advance again over it. Terminal moraines are thus sometimes pushed up into ridges.

Fig. 315 shows a small terminal moraine deposited during the final retreat of a glacier. In some valleys a succession of such moraines occurs. At or near the position of the ice-front at the period of maximum advance of the ice morainic deposits commonly

C. A. Cotton, photo.

Fig. 315.—Small terminal moraine in the Greenstone Valley, near Lake Wakatipu, N.Z. This view shows also a non-glaciated hanging valley.

occur on a larger scale, frequently damming the valleys to form lakes. Lakes Tekapo, Pukaki, Te Anau, Wakatipu, and, indeed, the majority of the lakes of the South Island of New Zealand, are held up to their present level by moraines. Such moraines are generally notched to a considerable depth by the gorges of the outflowing rivers, and have generally also been planed by them to some extent at higher levels (fig. 316).

C. A. Cotton, photo.

FIG. 316.—The moraine blocking the Lake Wakatipu valley at the south end (Kingston Moraine), partially planed and terraced by a river that was the former outlet of the lake.

C. A. Cotton, photo.

FIG. 317.—Arcuate terminal moraine of the Mueller Glacier, Southern Alps, N.Z. The waste-covered surface of the glacier (now shrunken) may be seen within the arc of stranded moraine.

A glacier debouching from a mountain-valley on to a lowland and there spreading to form a paw-like expansion deposits around its margin a long arcuate terminal moraine, which may hold up a lake after the disappearance of the ice. On a small scale such an arcuate moraine may be seen where the Mueller Glacier debouches into the wide Hooker Valley (fig. 317).

Shrinkage of a glacier in a valley that is not too steep-sided results in the stranding of its lateral moraines, which form distinct terraces on the valley-sides, sloping down the valley with the inclination of the ice-surface (figs. 277, 318, 319).

Stranded moraines, both terminal and lateral, consist of material of all sorts and sizes, from boulders as large as houses to the finest rock-flour, but the coarser material predominates. It is all deposited without sorting and without stratification. Some boulders are smooth and polished by attrition (see p. 317), while others (which have been carried on the surface of the ice) are quite angular. The proportion of rounded to angular boulders varies very much in different glaciers.

The topography of moraines is remarkable chiefly for its irregularity (fig. 318), organized valley-systems such as are produced by normal erosion being naturally absent. There are many undrained hollows forming lakes and tarns, or swamps when partially filled in. The moraines deposited in the Glacial period have generally been little modified since by normal erosion.

Erratics.—Glaciers did not always remain confined to the pre-existing valley-systems, but, where the ice-accumulation became thick enough, overflowed former divides, which, unless much worn down by glacial erosion, have become divides again after the disappearance of the ice. Much waste has, therefore, been transported by ice across existing divides. Boulders carried in this way from one valley-system to another, and, in general, those deposited by ice in positions to which they could not have been transported by normal agencies, if they are recognizable as such owing to the rock composing them being of a kind foreign to the districts in which they are dropped, are termed *erratics*. The perched block shown in fig. 313 is an erratic.

Glacial Drift.—Ice-sheets are most active in eroding near the centres of accumulation, and most active in depositing waste near their margins. In the intervening areas they erode in some places and

F. G. Radcliffe, photo.

Fig. 318.—Broad terrace formed by one of a series of lateral moraines deposited by the ancient Tasman Glacier, N.Z.

N.Z. Geological Survey, photo.

Fig. 319.—Lateral moraine deposited by the ancient glacier that excavated Boulder Lake, northern Nelson, N.Z.

deposit in others. The discontinuous sheet of waste thus spread over North America and northern Europe by the ice-sheets of the Glacial period is termed *drift.* It originated as subglacial moraine, and consists largely of *boulder-clay*, or *till—i.e.*, clay and fine sand with scattered pebbles and boulders of various sizes, these being often polished and striated. In some places the drift forms a sheet of fairly uniform thickness, reproducing the subdued topographic forms of the underlying surface; but frequently it varies irregularly in thickness and produces a new topography with weaker or stronger relief than that of the floor on which it lies.

J. Park, photo.

FIG. 320.—Kame-like ridges, partly of bed-rock and partly of drift, moulded by a local ice-sheet, near Arrowtown, Otago, N.Z. In the foreground there is a perched block.

Some of the drift is a roughly stratified deposit of fine material spread as fans or deltas by water draining from the ice as it retreated. In these "glacial sand-plains" basin-shaped hollows, termed *kettles*, are rather common, which are due to great blocks of ice in the drift melting and allowing the surface to sink in.

Certain more or less regular ridges or mounds of glacial drift are given names. *Drumlins* are elliptical or somewhat elongated low hills

of subdued outline either formed by deposition under the margin of an ice-sheet by which they were moulded into shape, or carved out of an earlier thick drift deposit by the ice readvancing over it. *Kames* are " mounds and short interlocking ridges with hollows, the depressions being either dry or filled with water " (H. E. Gregory). They are believed to have been deposited at or under the irregular edge of the ice-sheet during a halt in its retreat. *Eskers* are long sinuous ridges, even-crested and symmetrical in cross-profile, which are superimposed on other topographic features. They are composed of rather regularly stratified sand or gravel deposited by running water, probably by subglacial streams close to the margin of the ice.

A discontinuous sheet of drift, mainly till, is spread on the Arrow Flat, a broad flat-bottomed depression extending from Queenstown to Arrowtown, N.Z.* It occurs partly as a thin sheet over bed-rock and partly as elongated mounds best described as kames (fig. 320). This depression was occupied in the Glacial period by a broad field of ice that appears to have been almost stagnant as compared with the great glacier contiguous to it in the Lake Wakatipu Valley.

Glacial Lakes.—Lakes, both large and small, and innumerable tarns, are characteristic features of glaciated landscapes. Tarns occur in the scoured-out hollows of mamillated slopes, and on the uneven surfaces of morainic deposits (fig. 318), while some are enclosed by ramparts of waste carried by avalanches down the steep sides of glaciated valleys.

Some lakes, as previously mentioned, lie in rock-rimmed hollows (*rock-basins*), due to differential erosion by valley glaciers and ice-sheets, while others occur in valleys blocked by the deposition of morainic material. Many of the largest lakes—those occupying considerable lengths of the great overdeepened glaciated valleys—owe their origin to a combination of the two causes. Such lakes are generally very deep, and, though the actual barriers that hold them up to their present levels consist of moraine, the bottoms of the lakes are far below the levels of the bed-rock foundations on which the morainic dams rest.

Lake Wakatipu is a good example of a lake of this kind. Its greatest depth is about 1,240 ft., and it has a flat bottom and the trough-like transverse profile characteristic of glacially eroded valleys.

* J. Park, 60, No. 7, pp. 26–27, 30–31, 1909.

The morainic dam—Kingston Moraine (fig. 316)—that holds it up rests on bed-rock at no great depth, the lowest part of the rim of the rock-basin being not less than 1,000 ft. above the deepest part of the lake-bottom.

The rock-basins in valleys that have been occupied by trunk glaciers, like those in corries (p. 313), appear to be due to heavy glacial corrasion where the ice was thickest—*i.e.*, between the regions of active alimentation and active ablation (Ramsay, 70). Farther down the valleys, where the glaciers were dwindling, the thickness of the ice would be less, and so also would its weight and its ability to deepen the valleys. Thus reversed, or up-valley, slopes, giving rise to rock-basins 1,000 ft. or more in depth, are the rule rather than the exception towards the outlets of the valleys formerly occupied by the great trunk glaciers of mountain regions. The reversed slope of the floor does not imply a reversed slope of the ice-surface, in which case it would be necessary to suppose that a considerable portion of each glacier near the terminal face was forced uphill as a rigid mass by pressure transmitted through the ice from the valley-head. Reversed slopes of the ice-surface, though not unknown in existing glaciers, are uncommon and are likely to occur only on a small scale. The great glaciers that excavated lake-basins were thousands of feet in thickness where the ice was deepest, and, though the valley-bottoms sloped upward towards the terminal face, the ice-surface had everywhere a down-valley slope sufficient to maintain the glacial flow. Even in a water-stream it is only the water-surface that must slope always down the valley in order to maintain the flow: in the bottom of the channel there may be many holes and pockets.

The lakes formed by overdeepening of glacial valleys are, like all other lakes, transitory features of the landscape, being subject to filling and liable to be drained by lowering of the outlets, leaving shore-line features to testify for a time to their former existence (Chapter XXIX). In New Zealand, lakes formerly occupying large portions of the glaciated valleys of North Canterbury—*e.g.*, that of the Rakaia—have been drained by the cutting of gorges at their outlets (Speight, 74, p. 339). Some lakes, such as Lake Wakatipu, the bottoms of which have been excavated below sea-level, cannot be entirely drained in the current cycle unless they are first much reduced in depth by the accumulation of silt, and that is unlikely to occur until the lake-basins are nearly filled by deltas.

Ice-dammed Lakes.—Where tributary glaciers melt away or retreat some distance up their valleys, while glaciers still remain in the main valleys, forming dams of ice across the mouths of the tributary valleys, temporary lakes may occupy these, and may endure long enough to leave shore-line features as terraces on the valley-sides; and similar lakes of larger size are formed as an ice-sheet withdraws from a land-surface with a general slope towards the ice.

In New Zealand the former presence of two ice-dammed lakes in the mountains of Canterbury has been inferred from the occurrence of lacustrine silt-deposits (Haast, 49), but no topographic forms, such as shore-line features, connected with them have been described. The relation of the Murchison and Tasman Glaciers (fig. 267) suggests that the latter may have held up a lake in the abandoned part of the valley of the former (during the retreat of the terminal face of the glacier to its present position) until the lake was filled with outwash gravel, which now spills over along the channel of the outlet river flowing side by side with the Tasman Glacier.

The Post-glacial Cycle.—A post-glacial cycle of normal erosion is now current in those regions from which the ice of the Glacial period has recently disappeared. In this cycle the general surface has nowhere yet developed beyond the stage of youth, though parts of the courses of the larger rivers are roughly graded, so that they may be said to have entered on the stage of early maturity in the river cycle.

Generally speaking, the signs of post-glacial degradation are most apparent on steep upper slopes, such as arêtes and the walls of cirques and troughs, while in cirques, and especially on valley-bottoms, aggradation is in progress.

The present condition of cirques has already been referred to (p. 313). Generally the outflowing streams from corries and hanging valleys have not succeeded as yet in cutting more than insignificant notches in their lips (figs. 286, 308).

Frequently near the heads of small glaciated valleys, and occasionally (where steps are present) in larger ones, the floors exposed by the retreat of the ice have average declivities so steep that the water-streams flowing in them in the post-glacial cycle must cut downward in their effort to become graded. In such cases the bed-rock floors remain exposed, and are more or less deeply trenched by the post-glacial streams. Even in such cases, however, much waste

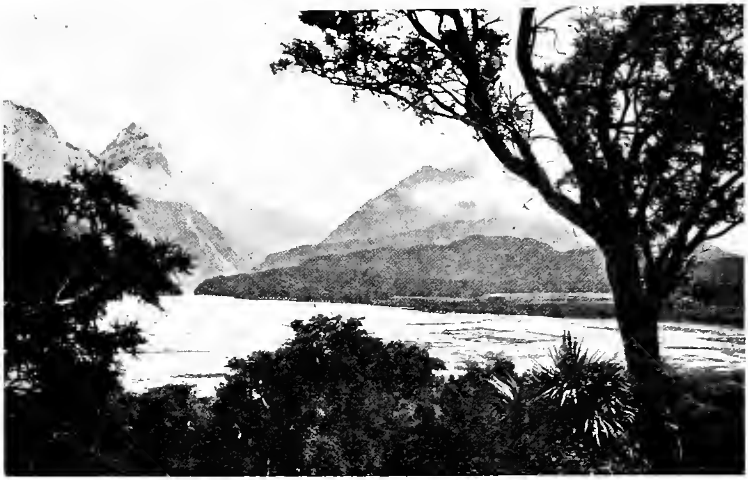
accumulates in the trough on either side of the stream-channel, for the bottom of a glaciated trough is more than wide enough to accommodate the water-stream, and the sides are too steep to be stable under conditions of normal weathering and erosion. When the protection given by the glacier is removed, the trough-walls crumble and are scored by ravines, so that talus slopes and alluvial cones mantle the lower slopes. The smooth, concave lower slopes of the sides of U-shaped glaciated valleys are due mainly to the accumulation of this talus (fig. 321). Where geological structures are favourable landslips occur, sometimes on a large scale.

R. Speight, photo.

Fig. 321.—U-shaped glaciated valley of the Otira River, Arthur's Pass, N.Z. The lower parts of the valley-sides are mantled by talus slopes.

Though the average declivities of the glaciated initial floors may be steep near valley-heads, occasional reversed slopes are common, giving rise to post-glacial lakes and tarns, which exist until drained or filled either by screes from the sides or by deltas at the heads.

The filling of these small lakes gives rise to some aggradation immediately up-stream from them; but much more extensive aggradation is found to be in progress as the larger valleys are followed down-stream, for the declivities of the bed-rock floors soon become very gentle, approaching the horizontal. A little farther down-



F. G. Radcliffe, photc.

FIG. 322.—The aggraded glaciated valley of the Dart, head of Lake Wakatipu, N.Z.

F. G. Radcliffe, photo.

FIG. 323.—Fluvio-glacial "gravel" among terminal moraines deposited by the Hooker Glacier, N.Z.

stream, indeed, in many valleys the glaciated floors slope up-stream, a condition which, as already noted, determines the existence of large consequent lakes in the post-glacial cycle, while others are due to the presence of barriers of terminal moraine. Where lakes due to one or other or both of these causes occur in the lower parts of the valleys they are rapidly reduced in size by the growth of deltas at their heads, and the growth of deltas is accompanied by aggradation farther up the valleys (p. 217). Even where there are no initial lakes—*i.e.*, no reversed slopes of bed-rock or morainic barriers —the declivities in large glaciated valleys are, in general, so gentle that the post-glacial rivers, heavily laden as they are with waste from the erosion of glaciated slopes, must aggrade them strongly.

The valleys abandoned by large glaciers in New Zealand are thus deeply aggraded. They have wide, gravel-covered bottoms, on which the rivers—*e.g.*, the upper Waimakariri, Rakaia, and Rangitata, in Canterbury, and the Dart, Routeburn, and others at the head of Lake Wakatipu, in Otago—wander in braided courses (figs. 200, 284, 322).

Part of the aggradation of glaciated valleys takes place while diminished glaciers still occupy the valley-heads, their moraines supplying much of the waste. In the Tasman Valley, for example, a wide aggraded valley-plain is actively growing and advancing as a delta into Lake Pukaki.

Aggradation in the Glacial Period.—When, in the Glacial period, valley glaciers had their maximum extension, gravel derived from their moraines was generally deposited in considerable quantity as alluvium on lowlands or in valleys adjacent to the glaciated region, for the glacier-fed rivers were so fully loaded with waste that they aggraded the pre-existing, non-glaciated valleys. Aggraded valley-plains thus produced in close association with glaciers are sometimes termed *valley trains*, and more widespread deposits form *outwash gravel plains*. It is probable that the Canterbury Plain was largely built of "outwash gravel" during the Glacial period.

In valley trains the water-laid gravel may sometimes be found, when traced up-stream, to merge into terminal moraine. The material that has been carried but a short distance by water may show an unusual proportion of large boulders and relatively little stream wear, while some stones may even retain glacial striae. Such gravel is termed *fluvio-glacial*. A similar association of water-laid with morainic waste may be seen close to existing glaciers (fig. 323).

Changes in Drainage due to Glaciation.—Though the majority of rivers, large and small, follow approximately the same lines in

the post-glacial as in the pre-glacial cycle, considerable changes in the drainage pattern may be brought about in various ways by glaciation.

Blocking of a drainage-channel by an ice-tongue thrust across it so as to form an ice-dammed lake causes a stream to take a new course where the lake overflows, either around the snout of the glacier forming the obstruction or through some gap in the surrounding hills, and when this condition persists long enough to allow the outlet gorge to be deeply cut the diversion of the stream may be permanent.

Another cause of changes in drainage is glacial "diffluence," where a glacier has split in two by spilling either over a pre-glacial divide or through a gap resulting from sapping of a cirque-wall. The channel of the distributary thus formed has been in some cases so deepened by the ice as to be followed by post-glacial drainage in preference to the former course, which may also be partially blocked by morainic deposits. The latter cause alone might conceivably pond a stream so that it would spill over along a new course.

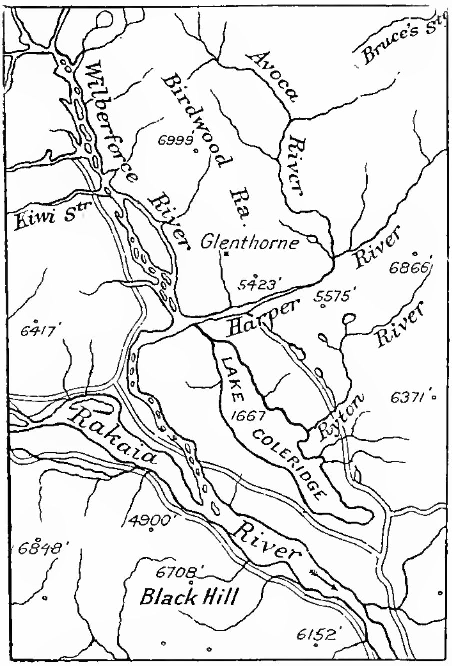


Fig. 324.—Map showing the diverted course of the Wilberforce River and the reversed drainage of Lake Coleridge, N.Z.

In the Southern Alps diffluence frequently took place in the widely extended glaciers of the Glacial period, and numerous departures from the pre-glacial drainage pattern have been noted, especially in the neighbourhood of the Rakaia Valley (74, p. 341). The pre-glacial course of the Wilberforce River, for example, was through the valley now occupied by Lake Coleridge, the drainage of which is now reversed (fig. 324).

CHAPTER XXIV.

VOLCANOES AND IGNEOUS ACTION.

Igneous action. Volcanic contributions to the atmosphere. Volcanic topography. Destructive volcanic action. Constructive volcanic action. Rock-forming materials emitted from volcanoes. Lava-sheets. Central eruptions and fissure eruptions.

Igneous Action. — *Volcanic action* is one phase of *igneous action*, the other phase being *intrusion*. While volcanic action consists in the emission of material from vents at the earth's surface, the term "intrusion" is applied to the injection of hot fluid rock into fissures and cavities, which are enlarged in the process (p. 11).

The hot fluid rock in the interior of the earth is termed *magma*. When it emerges on the surface it is termed *lava*. When it has solidified either on or beneath the surface as a result of cooling and the loss of its more volatile constituents, such as water and certain gases, it forms *igneous rocks*. The magma which solidified as the known igneous rocks, volcanic and intrusive, probably came from reservoirs at a depth of several miles, but not from a continuous liquid interior. There are reasons for believing that the central part of the earth, though very hot, is kept solid by the enormous pressure exerted by the weight of overlying rocks. It is, at any rate, rigid and immobile.

There has been igneous activity throughout all stages of the earth's long history. Volcanic rocks similar to those emitted as lavas by present-day volcanoes are found interbedded with the sedimentary rocks of all ages (fig. 325), and large intrusions of igneous rock, such as granite, are also of many different ages.

While it is known that volcanic action is a phenomenon that is not peculiar to the present period, there is no reason, on the other hand, to suppose that the igneous activity of the earth is dying out. For an immense period the activity seems to have been, on the average, about the same as at present.

Volcanic Contributions to the Atmosphere.—In addition to altering topography and spreading new deposits of solid material on the surface of the lithosphere, volcanic action supplies great volumes of gases to the atmosphere. Much water ejected as gas into the atmosphere is condensed and added to the ocean. Other gases—sulphur and compounds of sulphur, hydrochloric acid, and chlorides, for example—solidify or are soluble or are quickly oxidized to form soluble compounds, and are dissolved or washed out of the atmosphere by rain. Carbon dioxide, however, being

C. A. Cotton, photo.

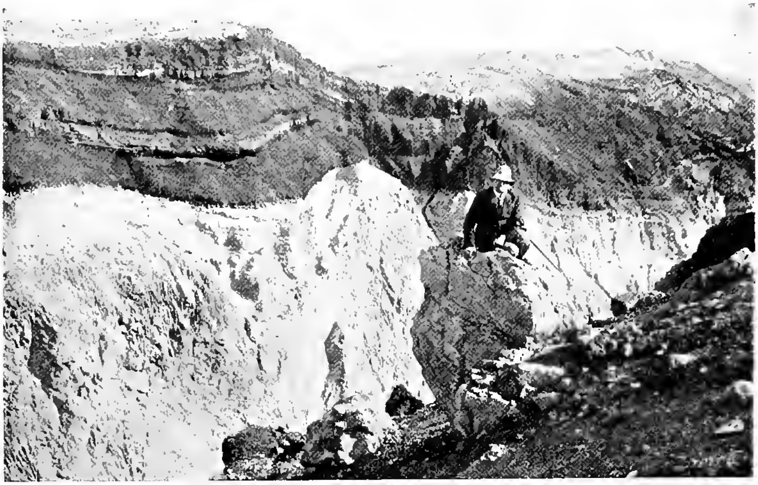
FIG. 325.—Ancient volcanic rocks, interbedded with sediments, and steeply tilted, outcropping to form a homoclinal mountain, Mount Lookout, Marlborough, N.Z.

soluble only to a limited extent, is added to the atmosphere unaltered. During geological time vast quantities of this gas have been taken from the atmosphere and stored in the lithosphere either in combination with lime—as limestone—or as carbon from which the oxygen has been separated—in that case forming the chief constituent of coal. The formation of carbonates by the action of carbon dioxide from the atmosphere is an important phase of the chemical weathering of rocks, and much of the carbon

dioxide so used becomes locked up in the rocks. Though plants are constantly taking carbon dioxide from the atmosphere, this is normally returned when the organic carbon compounds formed decay again. When, however, vegetable matter decomposes away from oxgyen so as to form peat or coal this reoxidation of the carbon does not take place, and so it is not returned to the atmosphere.

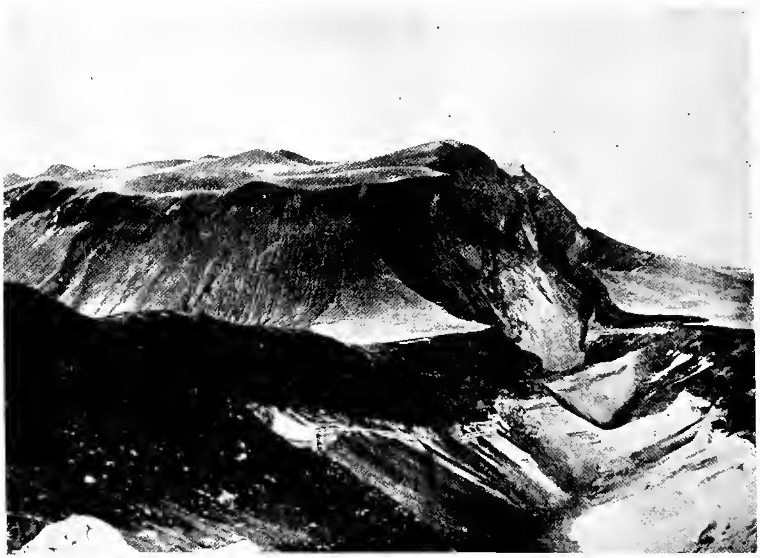
The amount of carbon dioxide in the atmosphere is quite small —three parts in ten thousand. The amount of carbon locked up in the rocks in the form of limestone and coal, all of which is derived from atmospheric carbon dioxide, however, represents a volume tens of thousands of times as great as the volume of carbon dioxide now in the atmosphere. According to an old theory, this enormous volume of carbon dioxide is regarded as having been all in the atmosphere at one time in an early stage of the earth's history. Before the removal of the greater part of the carbon from the atmosphere, however, the earth was clothed with vegetation and inhabited by animals differing but little from those now living, and it seems impossible that these could have existed in an atmosphere so different from that in which plants and animals are now adapted to live. Moreover, the nature of the sediments formed during past geological periods indicates weathering under atmospheric conditions similar to those now ruling. We are therefore compelled to believe that volcanic action, which is to-day supplying carbon dioxide to the atmosphere, has in the past supplied in this way, little by little, all the carbon that is now present in the limestone and coal of the lithosphere. The proportion of carbon dioxide in the atmosphere, while it has, no doubt, varied from time to time, may never have been very markedly different from what it is to-day.

Volcanic Topography.—Those materials which are ejected from volcanoes in the solid state, together with the fluid rock which after flowing out quickly cools and solidifies, build new topographic forms. Large areas of the earth's surface owe either the actual forms they now exhibit or the initial relief from which those forms were sculptured to the accumulation of volcanic ejectamenta. In many of these regions volcanic action is now extinct, but the origin of the material and of the forms built of it is quite clear from analogy with the products of volcanoes that are still active.



B. C. Aston, photo.

Fig. 326.—Rift formed by the Tarawera eruption in 1886. The dark upper layers consist of material ejected during the eruption.



N.Z. Geological Survey, photo.

Fig. 327.—Mount Tarawera, showing the "chasm"—part of the rift blown out by the eruption of 1886.

Far-reaching changes in drainage may result from the accumulation of volcanic ejectamenta. In New Zealand, for example, it has been suggested by Cussen that the Waikato River was thus turned aside from a former course with an outlet to the Bay of Plenty.

Volcanic rocks, as a rule, when weathered, produce excellent soils, and thus there is commonly a large population in regions of volcanic relief. Rich soils are found even on the flanks of some of the larger active volcanoes, and it is the temptation offered by these that induces settlement in such places and leads often to loss of life when an eruption occurs.

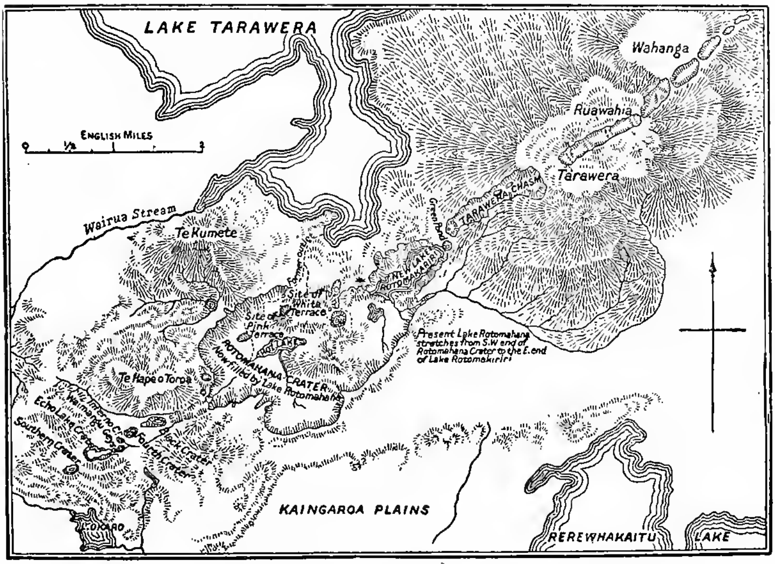


FIG. 328.—Map of the Tarawera volcanic rift soon after the eruption of 1886. After Bell (*Geographical Journal*, vol. 40, 1912).

Destructive Volcanic Action.—Volcanic action not only builds new forms, but also destroys those already in existence. In New Zealand, in 1886, for example, the Tarawera eruption blew out a rift, or line of elongated pits (figs. 326–328), forming a nearly continuous trench about nine miles long, with a mean width of about an eighth of a mile and a depth varying from 300 ft. to 1,400 ft. (Smith, 73). The rift passes across the top of Mount Tarawera (fig. 327), which is a mesa of volcanic rocks (p. 96), and

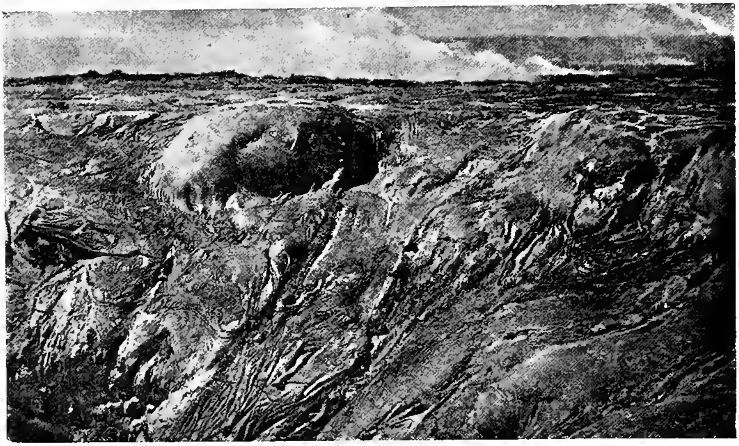


FIG. 329.—Surface of a flow of "pahoehoe" lava, Savaii, Samoa.

R. Speight, photo.

FIG. 330.—Scoria-covered surface of lava of the "aa" type. Face of a solidified lava-flow from the Red Crater into the central crater of Tongariro, N.Z.

continues in a south-westerly direction for some distance, becoming wider and shallower, and forming the basin of the present Lake Rotomahana, which is much larger than the lake of the same name existing before the eruption. The fragments blown out by the explosion came to rest round about. Around Lake Rotomahana there is a thick deposit of a mixture of rock-fragments and mud derived entirely from the pre-existing rocks. This buried and destroyed the vegetation over a large area, and wrecked several Maori villages. More than a hundred persons were killed, and the loss of human life would have been much greater but for the fact that the district was very sparsely peopled.

Constructive Volcanic Action. — When topographic forms and not vegetation nor the works of man are considered, however, the destructive action of vulcanism is slight as compared with its constructive activity. Great mountains, either singly or in groups, are built up, and large areas are flooded with lava (fig. 331, *b*) or deeply buried beneath fragmentary material. This is a "volcanic accident," referred to in Chapter XVI, by which the progress of a cycle of erosion is cut short and a new initial surface prepared upon which erosion begins again.

Rock-forming Materials emitted from Volcanoes.—The materials emitted from volcanoes (in addition to the gases mentioned above) are both liquid and solid. The liquid material, or lava, consists of a mixture of minerals, chiefly silicates, in a state of fusion, or of solution the one in the other. It varies widely in mineral, and hence also in chemical, composition, and so forms on solidification a considerable variety of rocks. By the time the lava flows out on the surface it has lost a great part of the gaseous constituents which formed an integral part of the magma within the lithosphere, and practically all of the remainder escape during cooling.

The temperature of lava when emitted is generally between 1,000° C. and 2,000° C., and not far above the solidifying point. It is still sufficiently liquid to flow, but the liquidity is very variable, varying to some extent with the temperature, but depending to a much greater extent on the kind of lava.

Some flows of very fluid lava freeze over quickly, and the crust hardens with a continuous, smooth, though somewhat uneven, surface, beneath which the liquid lava continues to flow ("pahoehoe"

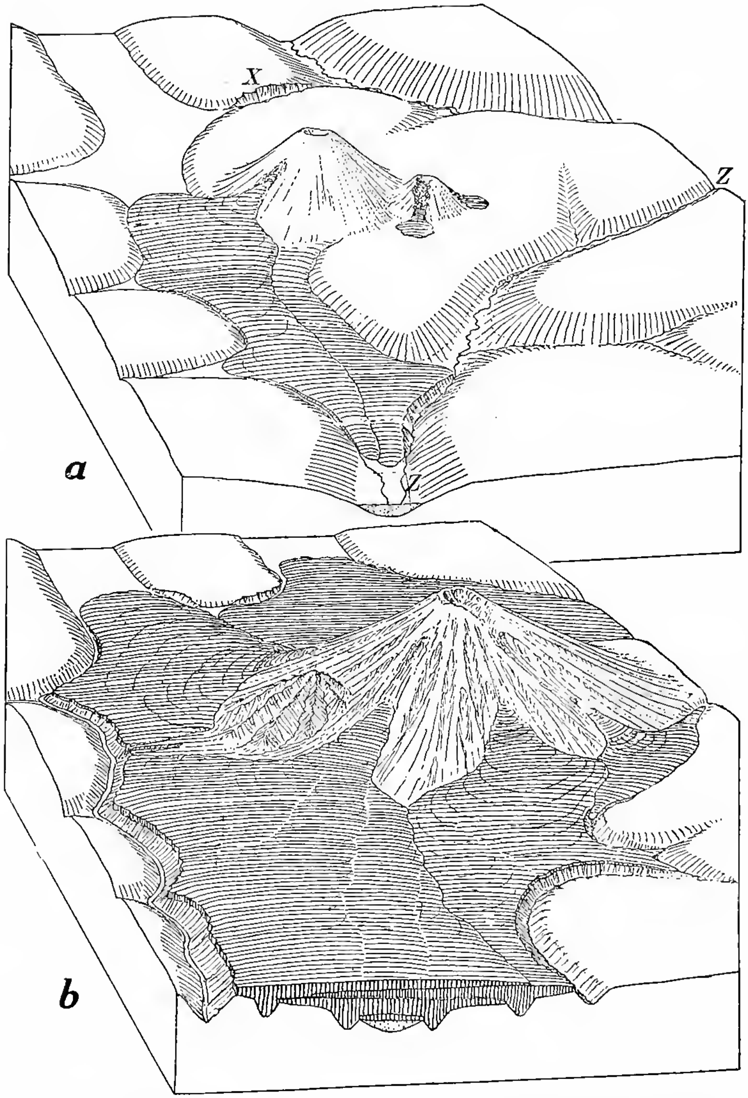


FIG. 331.—Volcanoes and lava-sheets overspreading a land-surface and obliterating the former relief. (Two of a series of eight diagrams used by Professor W. M. Davis in his *Practical Exercises in Physical Geography* to illustrate the growth of land-forms due to volcanic action, and their dissection by erosion.)

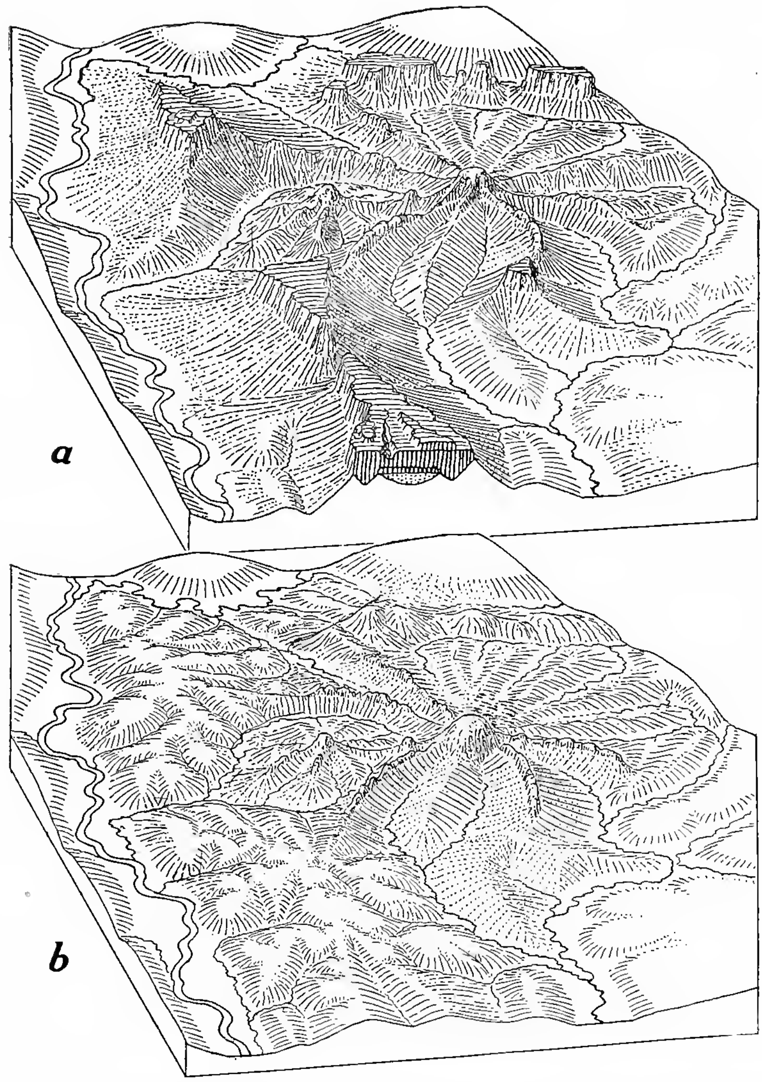


FIG. 332.—Later stages of the landscape shown in fig. 331, in which after the cessation of volcanic activity, the volcanic accumulations shown there have been much dissected and eventually removed by erosion. After Davis (two of the series of diagrams referred to in the explanation of fig. 331.)

type of lava, fig. 329). Sometimes this crust presents the appearance of a series of immense globules budding one from another; in other cases it is drawn out into a "ropy" surface during solidification. The still liquid lava may flow out from beneath portions of the solidified crust, leaving caverns or tunnels. Such tunnels are found in New Zealand in the lava-flows of Rangitoto Island and the Auckland Isthmus.

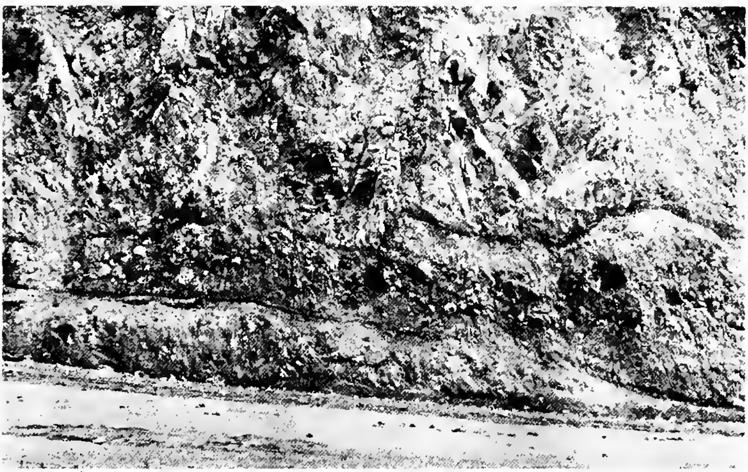
Other lava-flows (of the "aa" type) advance and cool with a surface composed of blocks of cinder-like, very vesicular solidified rock termed *scoria*. An "aa" flow is very viscous, and solidifies with a steep front (fig. 330). The blocks of scoria are generally rounded by rolling over one another.

The solid material ejected from volcanoes is in part scoria similar to that formed on cooling lava-flows, and in part *tuff*, or fine "ashes." Eruptions of scoria take place owing to the formation of a crust of solidified scoria on the surface of lava in a crater, which is later blown out by gases (principally steam) that have accumulated under it. This may take place repeatedly, and so a thick mass of scoria may accumulate around the vent. Scoria in small fragments is termed *lapilli*. The scoria from acid—*i.e.*, siliceous—lava is often so thoroughly inflated with gas that it is a solidified froth. It is then termed *pumice*. Mixed with scoria—amongst that, for example, forming the volcanic hills near Auckland—*volcanic bombs* are sometimes found. They originate as fragments of the skins of enormous gas-bubbles which rise to the surface of viscous lava in a crater and there burst. The fragments of lava are hurled through the air, rotating meanwhile and assuming a spheroidal form with twisted, corkscrew-like ends. By the time they fall to the ground they have cooled and solidified sufficiently to retain their shape, except that they are generally somewhat flattened by the impact of their fall.

Tuff consists of small fragments of lava—often isolated crystals of minerals—separated by explosion, projected into the air, sometimes to a great height, carried by the wind, and spread as a layer over a wide area. The smoke-like clouds emitted from volcanoes consist in part of tuff-particles (fig. 348). They deposit a rain of mud, and when newly fallen and saturated with water tuff is often described as "volcanic mud" (figs. 65 and 208). Layers of pumice and tuff scattered by explosive eruptions are found on the surface

over the whole of the central and much of the eastern portion of the North Island of New Zealand. The tuff and lapilli distributed by the Tarawera eruption (1886) form a recognizable layer over an area of about four thousand square miles. In the immediate vicinity of the rifts on Mount Tarawera the deposit is 170 ft. thick, and consists of large fragments of scoria (fig. 326). Had this material been ejected less violently it would have accumulated around the vents to form volcanic mountains of considerable size.

Lava-sheets.—Great sheets of very fluid lava spreading and solidifying over large areas, as shown in fig. 331, *b*, give rise to



C. A. Cotton, photo.

FIG. 333.—A succession of lava-sheets exposed in a road-cutting, Dunedin, N.Z.

volcanic plateaux. The surface is generally moderately smooth, though it may be diversified by scattered hills of scoria (scoria cones, p. 343). Such plateaux, especially if built of a thick mass or succession of sheets of lava, are resistant to erosion, but they eventually become dissected. When the base of the lava is above base-level, and the sheet is cut through by erosion, mesas are formed (fig. 332, *a*), for the rocks beneath are generally weaker than the lava sheets; and as erosion proceeds the mesas are cut up into buttes of diminishing size, which will eventually disappear (fig. 332, *b*).

Central Eruptions and Fissure Eruptions.—While the majority of lava-flows of limited extent have come from the orifices of the pipe-like conduits that are surmounted by volcanic mountains, some of the more extensive plateau-forming sheets seem to have welled out from gaping fissures. Eruptions of the former type are termed *central eruptions*, of the latter *fissure eruptions*. A fissure eruption occurred in Iceland in 1783, when a flood of lava was emitted which flowed forty miles; and the eruption of Tarawera (1886), referred to previously in this chapter, was distinctly of the fissure type, though in that case outflow of lava from the fissure did not take place. The majority of volcanoes are, however, of the central type, though a series of the conduits forming the vents of central eruptions are often ranged in line in such a way as to suggest that at depth they are connected with a continuous fissure. Such a linear arrangement is found in New Zealand in the group of volcanoes, still to some extent active, that extends from White Island, in the Bay of Plenty, through the Rotorua – Tarawera district and Lake Taupo to Mounts Tongariro, Ngauruhoe, and Ruapehu—the Taupo volcanc zone (Hochstetter, 51, 52).

In New Zealand a great mass of lava rocks consisting of many sheets, some of them of limited extent and some more wide-spreading, some made of the more viscous kinds of lava and some of the more fluid, forms the hills surrounding Otago Harbour (fig. 333). The mass is sculptured by normal erosion to mature relief, with a somewhat coarse texture of dissection (figs. 63, 389, 404), and the valleys in it are partly drowned by submergence (Chapter XXVIII).

CHAPTER XXV.

VOLCANOES AND IGNEOUS ACTION (*continued*).

Volcanic mountains. Springs associated with composite cones. Forms of craters. Erosion of volcanic mountains. Inversion of topography. Volcanic skeletons. Minor topographic effects of volcanic action. Hot springs. Geysers. Laccolitic mountains.

Volcanic Mountains.— Typically the accumulation of volcanic material about a central vent produces a mountain with the conical form (fig. 331) that is generally regarded as typical of volcanoes. Volcanic cones vary in shape according to the nature of the material ejected and the nature of the eruptions that have taken place—whether quiet or paroxysmal. Typically there is a pit or cup-shaped hollow, the *crater*, truncating the apex of the cone. This is the opening of the volcanic pipe through which the ejected materials have come to the surface. Typically, also, the lower slopes of the cone—below the convexity of the crater-edge—are concave in radial profile, the slope becoming gentler with increasing distance from the crater, around which the coarser ejected fragments are steeply piled up.

Some volcanic mountains are very bluntly truncated, owing to the whole top of the original cone having been blown away by an explosive eruption. In New Zealand Mounts Tongariro and Ruapehu (fig. 334) are described as having suffered in this way (Speight, 73A). Tongariro has now a summit-area of about twenty square miles, diversified by explosion craters (some of them occupied by lakes, fig. 335), small cones of more recent growth, and small lava-flows from these (fig. 330).

The steepness of volcanic cones varies within wide limits. The steepest are those built entirely of scoria—*scoria cones*, or "ash" cones (fig. 336). The angular, rubbly scoria comes to rest on the sides of the cones at slopes as steep as 35°. Scoria cones are numerous in and around the city of Auckland (fig. 337), and many scattered cones occur throughout the North Auckland district.

F. G. Radcliffe, photo.

Fig. 334.—Mount Ruapehu, N.Z., a volcanic mountain, the top of which has been blown away by an explosive eruption, seen from Horopito.

L. Cockayne, photo.

Fig. 335.—Part of the irregular plateau formed by the blowing-away of the summit of Mount Tongariro, N.Z., showing the Blue Lake, occupying an explosion crater.

When the cone consists of *lava* the slope is very variable, depending on the fluidity at the time of outflow. Thus "cones" of very viscous lava are dome-shaped rather than conical, while more fluid lavas build symmetrical cones with very gentle slopes. A lava cone of the latter kind forms Rangitoto Island, at the entrance to Auckland Harbour (fig. 338).

Cones of *tuff*, of which there are examples near Auckland (figs. 337, 339), have extremely gentle slopes and form flat rings

C. A. Cotton, photo.

FIG. 336.—A scoria cone, Mount Maungatapere, Whangarei, N.Z.

around very large craters. Cones of scoria are sometimes built within the craters of large tuff cones.

Most large volcanic mountains—all those in New Zealand, for example—are *composite cones*, built of alternating layers of scoria and of lava which was sufficiently viscous to solidify on the scoria slopes (fig. 340). Within the cone there are usually also numerous dykes (p. 11) radiating from the central pipe, and due to the penetration of the molten rock from it into fissures which have resulted, perhaps, from the shaking produced by explosive eruptions

(fig. 341). Lava sometimes reaches the surface by way of one of these fissures, and a vent is opened on the flank of the volcano.

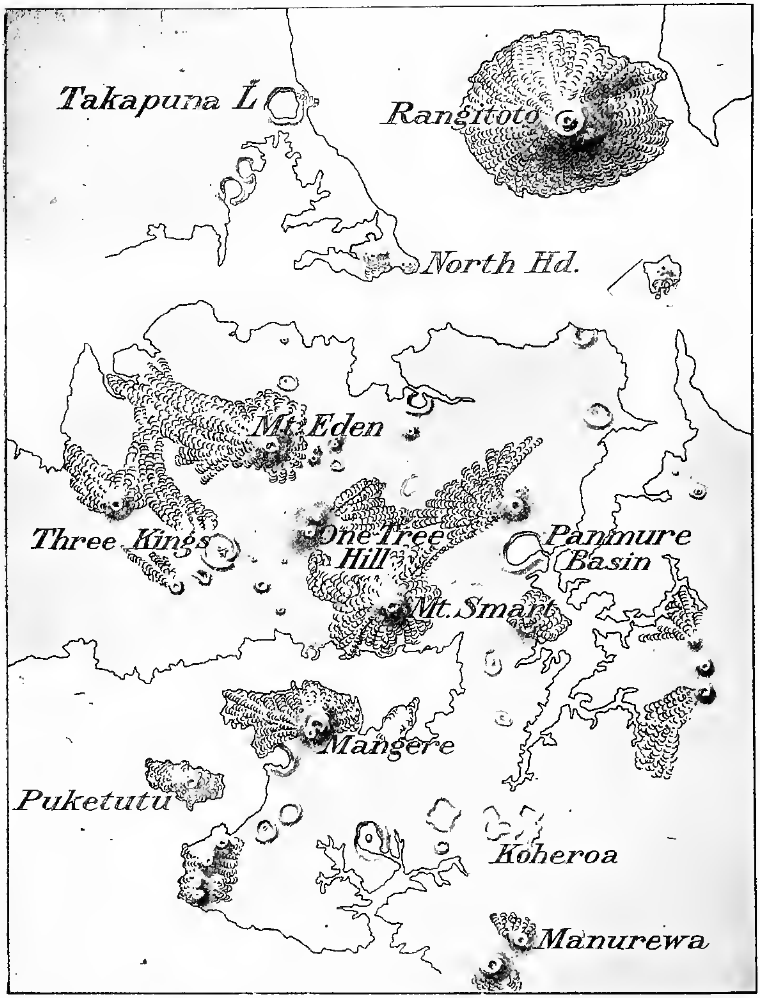


FIG. 337.—Volcanoes of the Auckland Isthmus, N.Z. From Marshall's *Geology of New Zealand.*

Outflow of lava takes place, or, perhaps, a *parasitic cone* is built, composed principally of scoria (fig. 342). In some cases the main

centre of eruption shifts to a new vent thus opened, and about this a cone is built which would at first be classed as "parasitic," but which grows so as to overtop the cone surrounding the original vent (fig. 331), and may entirely bury it.

Springs associated with Composite Cones.—The alternation of beds of porous scoria with impermeable lava-sheets leads to the rather common occurrence of large springs in volcanic districts. Rain-water sinks into loose scoria on the slope of a cone and is led away under a sheet of lava, to emerge again from beneath its lower edge. The water is frequently collected into streams

Home Studios, Takapuna, photo.

Fig. 338.—Rangitoto Island, Auckland, N.Z., a lava cone with a scoria cone within its crater.

flowing under considerable pressure beneath the lava-sheet, and so may gush forth as a voluminous spring. On the flanks of Tongariro and Ruapehu streams of considerable size (*e.g.*, the Waihohonu, fig. 343) take their rise in springs of this kind.

Forms of Craters.—The craters of central volcanoes are always approximately circular (figs. 346, 347). Their size is determined not by the size of the cones formed around them, but rather by the diameter of the pipe beneath. The craters of scoria cones of small dimensions are thus relatively large. The craters of scoria cones

J. A. Bartrum, photo.

FIG. 339.—Takapuna crater, Auckland, N.Z., occupied by Lake Takapuna. Though lava occurs at one side (on the left in the photograph), the crater-ring consists mainly of tuff.

N.Z. Tourist Department, photo.

FIG. 340.—Mount Ngauruhoe, N.Z. (snow-covered), a composite cone that is still growing.

are also bowl-shaped, for some of the ejected scoria falls within and some without the crater-rim, the former building up the inner slope of the crater while the latter is adding to the outer slope of the cone. The scoria is thus stratified parallel to the outer slope and the crater slope. During moderate activity fragmentary material is deposited within the craters of large volcanoes also, forming layers sloping inward (fig. 345), but when there is a particularly violent explosive eruption, and the whole apex of the cone is blown away, the crater thus enlarged has precipitous walls in which the edges of the strata parallel to the outer slope are exposed (fig. 346).

C. A. Cotton, photo.

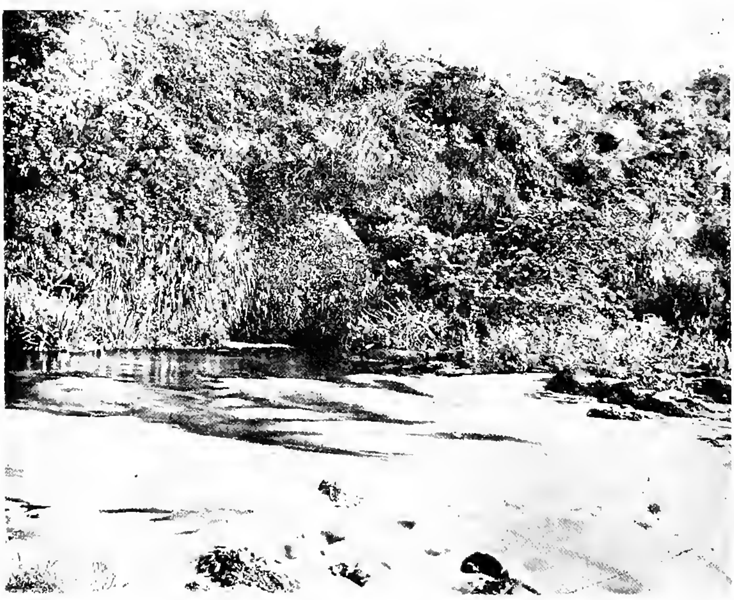
FIG. 341.—Small hogback ridge formed by the outcrop of a dyke penetrating the lava-sheets and scoria-beds of one of the volcanic mountains forming Banks Peninsula, N.Z.

The present crater of Ngauruhoe is situated within a partly filled-in explosion crater, the wall of which is still high and precipitous on the south-east side (figs. 346, 347). The cone is thus rather bluntly truncated.

Large explosion craters are sometimes called "calderas," but more strictly the term *caldera* implies a large crater—possibly an explosion crater—breached at one side by an eroded valley and much modified and enlarged by stream erosion. In this sense the

F. G. Radcliffe, photo.

FIG. 342.—Mount Egmont, N.Z., a composite volcanic cone, with a parasitic cone, Fantham's Peak, on its flank, as seen from Stratford, Taranaki.



L. Cockayne, photo.

FIG. 343.—Spring at the edge of a lava-sheet, forming the source of the Waihohonu Stream, near Mount Ngauruhoe, N.Z.

harbours of Lyttelton (fig. 349) and Akaroa are calderas that have been converted into arms of the sea by submergence (Speight, 75). Lakes Taupo and Rotorua and other large lakes in the volcanic district of the centre of the North Island of New Zealand do not appear to be explosion cavities, but have been caused more probably by local subsidence due in some way to volcanic action. Many of the small lakes of that district seem, however, to occupy craters formed by explosive eruptions.

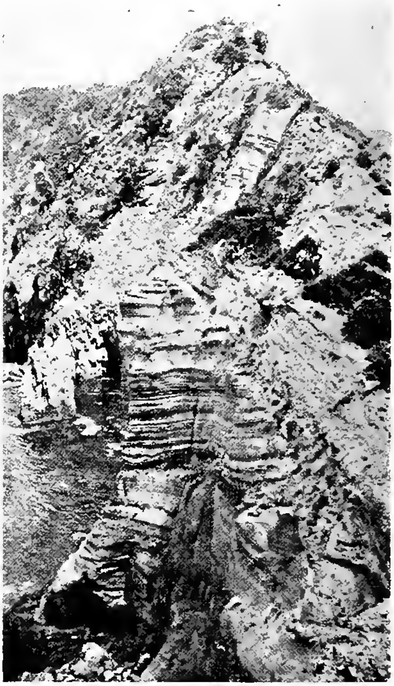
F. G. Radcliffe, photo.

FIG. 344.—Part of the snow-filled crater of Mount Egmont, N.Z.

Some abnormally large, steep-walled crater-rings—"calderas" in one sense in which the term is used—are regarded as due to collapse and in-sinking of the tops of volcanoes, taking place possibly as a result of exhaustion or drawing-off of the lava formerly filling reservoirs beneath the mountains. Such "calderas" are occupied by lakes (as in the case of Crater Lake, Oregon, U.S.A., a well-known example), or they may be partly filled by the ejectamenta from small volcanoes built up within them. A large crater, five

miles in circumference, on Mayor Island, Bay of Plenty, N.Z., is probably of this nature (fig. 350). The wall of this "caldera" is not breached by a stream, and drainage takes place underground through porous beds of pumice and lapilli. The walls of a "caldera" due to subsidence are curved fault-scarps, but these are not readily distinguished from the scarps bounding cavities due to explosion.

Erosion of Volcanic Mountains.—Even growing cones of lapilli and loose fine scoria are seen to be dissected by very numerous radial consequent ravines (fig. 340). Similar drainage-systems are developed on lava cones and on cones of coarser scoria, though much more slowly, because the material is more resistant and also because the scoria or the scoriaceous surface of lava is so porous that water sinks quickly underground, and few surface streams are formed.



C. A. Cotton, photo.

FIG. 345.—"Ash" beds sloping down (to the right) into a crater, Mayor Island, N.Z. The section of the beds has been exposed by marine erosion.

At a somewhat later stage in the dissection of a cone the number of consequent streams is reduced by the process of abstraction, and those that survive in the struggle for existence have cut large and deep ravines, and have some insequent, as well as abstracted consequent, tributaries. On the slopes of a composite cone some short subsequents, along weak scoria layers, may be developed also, leaving intervening homoclinal ridges of lava. This is the stage of dissection reached on the flanks of the two large volcanic mountains forming Banks Peninsula (figs, 207, 351). The "high" islands

FIG. 346.—The crater of Ngauruhoe, N.Z.

of the tropical Pacific—Rarotonga (fig. 352), for example—are also examples of maturely dissected volcanoes.

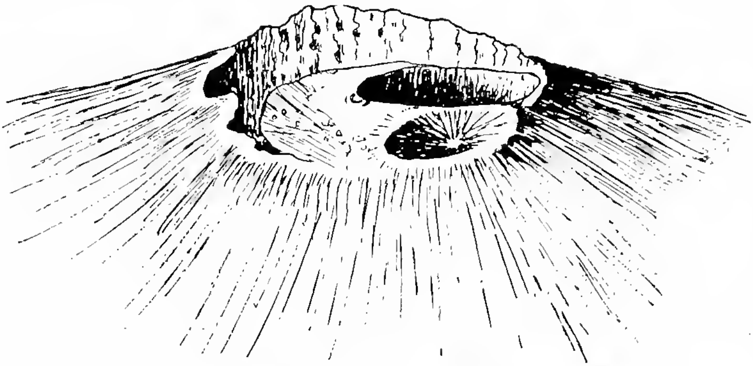


Fig. 347.—The crater of Ngauruhoe in 1906. (After Marshall.)

F. G. Radcliffe, photo.

Fig. 348.—The cone of Ngauruhoe, showing smoke-like cloud of fumes and tuff-particles emitted during an eruption.

Inversion of Topography.—Sometimes dissection proceeds to some depth during periods of inactivity, when a volcano is *dormant*, though not *extinct*. When activity is renewed in such a volcano

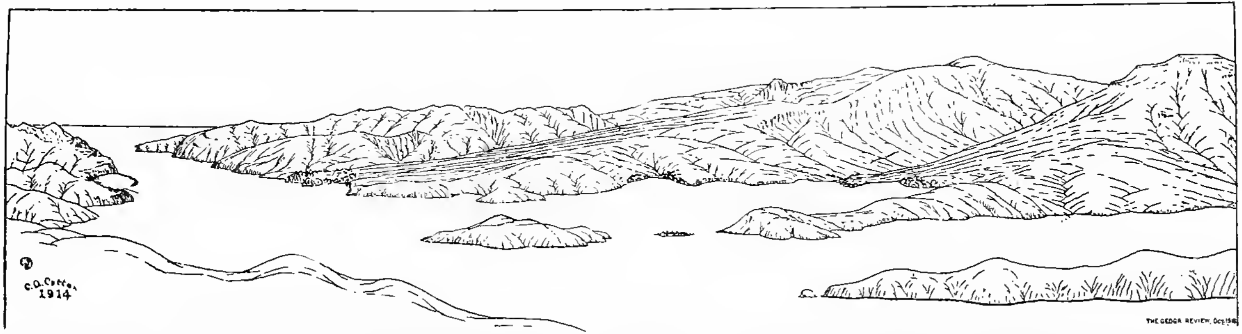


FIG. 349.—Port Lyttelton, N.Z., a valley-system eroded in the heart of an ancient volcano and then submerged. The even slope down to the water in the centre is the surface of a lava-flow of later date than the erosion of the valley-system.

C. A. Cotton, photo.

FIG. 350.—Part of the crater-ring enclosing the "caldera" on Mayor Island, Bay of Plenty, N.Z. To the left is the slope of a scoria cone built within the ring. The lowest parts of the floor are occupied by lakes.

the eroded ravines are filled up again. If lava is emitted the ravines will be occupied by lava-flows, and, unless the lava is of an exceptionally mobile, fluid kind, these flows solidify on the mountain-side, each with a convex surface (fig. 353). They then become divides, and new ravines are excavated between them on

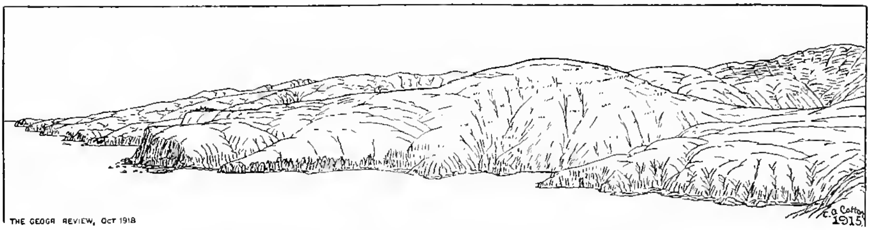


Fig. 351.—The northern side of Banks Peninsula, the flank of a large volcano, maturely dissected, partly submerged, and cliffed by the sea.

C. A. Cotton, photo.

Fig. 352.—Rarotonga Island, a maturely dissected volcanic island with a fringing reef of coral.

the sites of the former ridges. Thus the sites of streams have become divides, and divides have given place to streams. This is termed *inversion of topography.*

Volcanic Skeletons.—After the cone of an extinct volcano is maturely dissected it is progressively destroyed, and, as the cycle of

erosion proceeds towards old age, the land-surface may be worn down to a level beneath the base of all the volcanic deposits. Even when this takes place, however, some traces of volcanic action

F. G. Radcliffe, photo.

FIG. 353.—View of Mount Egmont, N.Z., showing convex lava-flows on its flank.

remain, for the pipe by way of which lava formerly reached the surface will be plugged with either compact solidified igneous rock or with agglomerate, a mass of blocks of lava. This forms a *neck*. It is highly resistant to erosion, and, if it passes through weaker formations, remains projecting as a rugged peak until late in the cycle of erosion (fig. 332, *b*). There are frequently also dykes of resistant igneous rock perhaps radiating from a neck, or necks (fig. 332, *b*; also fig. 2), which may stand out for a long period as ridges.

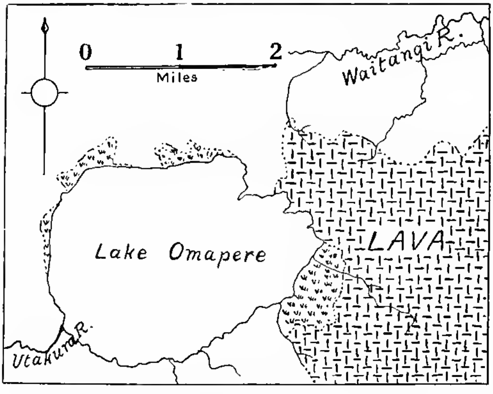


FIG. 354.—Lake Omapere, North Auckland, N.Z., the result of ponding of a stream by a lava-flow. (After *N.Z. Geol. Surv. Bull No. 8.*)

F. G. Radcliffe, photo.

Fig. 355.—Waitangi Falls. Bay of Islands, N.Z. The river is compelled to flow over lava that has solidified in its valley.

C. A. Cotton, photo.

Fig. 356.—Wairua Falls, North Auckland, N.Z. These falls have receded some distance up-valley from the edge of the lava-flow over which the river has been compelled to take its course.

Minor Topographic Effects of Volcanic Action.—Small outflows of lava, insufficient to change the whole aspect of the topography of a region (fig. 331, *a*), are yet capable of introducing important modifications into the course of the normal cycle. The lava makes its way into valleys, which it blocks, ponding streams and in some cases compelling them to spill over divides and take new courses (*X*, in fig. 331, *a*). Lake Omapere, in North Auckland, N.Z., has been formed owing to the blocking of a river-valley (Waitangi River, fig. 354) by lava, and the lake now spills over through an

N.Z. Tourist Department, photo.

Fig. 357.—Cone of siliceous sinter surrounding the orifice of a small geyser, the Crow's Nest, on the bank of the Waikato River, near Taupo, N.Z.

ungraded channel into the head of the Utakura River. Thus the main divide between drainage to the east and west coasts has been shifted several miles.

In other cases the streams follow approximately their former courses, and flow either by the side of the lava-flow, if its surface is convex (*ZZ*, fig. 331, *a*), or over the top of it, as in the case of many valleys in the North Auckland district that are occupied by small *lava plains* formed by the solidification of very fluid lava with a nearly horizontal surface. In the latter case falls are formed at the down-

N.Z. Tourist Department, photo.

FIG. 358.—Boiling mud-spring, Rotorua, N.Z.

N.Z. Tourist Department, photo.

FIG. 359.—A mud volcano at Waiotapu, N.Z.

valley ends of the lava-sheets, and in all cases the streams must regrade their courses. The Wairua, Whangarei, and Waitangi Falls, in the North Auckland district (figs. 355, 356), are due to this cause. In that district the small lakes formed by the ponding of the streams have generally been filled up to form swampy flats.

Hot Springs.—In some volcanic districts *fumaroles* (steam-jets) and *hot springs* occur abundantly. By some this thermal activity is considered to be an indication that the intensity of volcanic action is waning in such districts. The hot water and steam which supply the hot springs and fumaroles may be wholly derived from ordinary ground-water that has come in contact with hot rocks beneath the surface; but in most cases probably some water is being given off as steam from an underlying body of solidifying

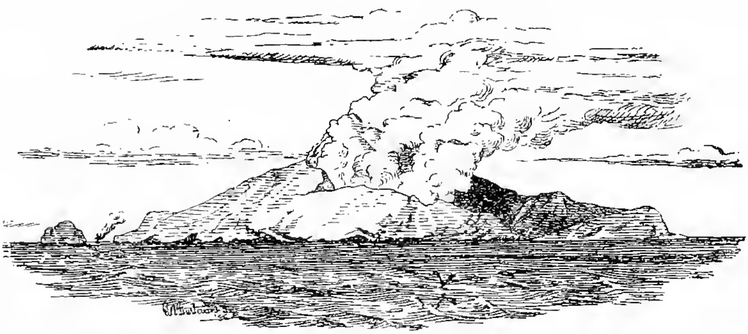


Fig. 360.—White Island, Bay of Plenty, N.Z. (from a sketch by Mrs. C. Alma Baker). After S. Percy Smith.

igneous rock. A small quantity of this superheated steam is sufficient to heat up a considerable volume of ground-water.

The heated water brings to the surface quantities of mineral substances in solution, among which is silica. The silica is deposited around the vents of the hot springs as an incrustation of *siliceous sinter*, protecting the ground from erosion and sometimes building conspicuous mounds (fig. 357). Sinter-deposits form the surface in parts of the Rotorua and Taupo districts, and the celebrated Pink and White Terraces, at Rotomahana, which were destroyed by the Tarawera eruption (1886), were also built of siliceous sinter.

Where the conduits are lined with sinter hot springs emerge as clear streams. In other cases steam bubbles through mud formed

N.Z. Tourist Department, photo.

FIG. 361.—Wairoa Geyser, Whakarewarewa, N.Z.

from volcanic rock decomposed by the hot acid water, and ground to an impalpable paste by the constant churning caused by the rising steam (fig. 358). Around particularly active springs this mud is built into small cones termed *mud volcanoes* (fig. 359).

A volcano the activity of which has dwindled to the emission of steam from points within the crater is termed a *solfatara*. White Island, a volcano in the Bay of Plenty, has reached the solfataric stage (fig. 360). There is often a hot lake within the crater, as in the case of Ruapehu.

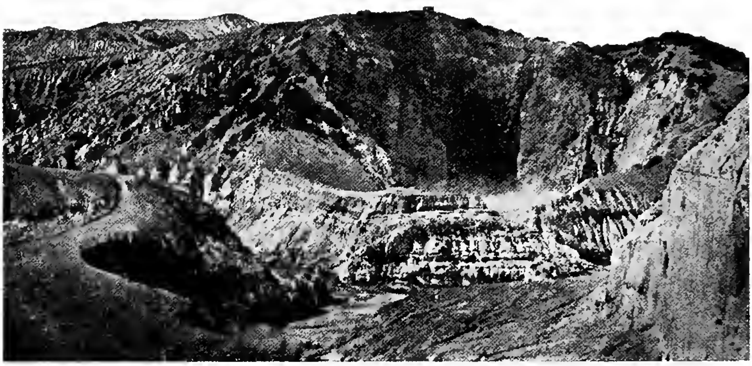
Muir and Moodie, photo.

Fig. 362.—Waimangu Geyser, near Lake Rotomahana, Rotorua district, N.Z. (no longer active).

Geysers.—A hot spring from which a column of water is shot into the air at regular or irregular intervals is termed a *geyser* (figs. 361, 362). The condition necessary for geyser-action is the presence of an open pipe leading down from the vent (opened perhaps by a flowing spring or a steam-jet), which is sufficiently narrow as compared with its depth to prevent free convective movement of the water that stands in it, as it is heated to the boiling-point by steam from below. Boiling will take place at a lower temperature at the surface of the water than at any point below the surface, for the

pressure increases with the depth of water, and the boiling-point rises with increasing pressure: the greater the depth below the surface, therefore, the higher the boiling-point. If mixture of the water and equalization of temperature by convection currents is prevented, the temperature of the water in the deeper part of the tube may rise considerably higher than the boiling-point at the surface, and yet none of the water be boiling.

When, next, some of the water in the lower layers is heated to the boiling-temperature appropriate to its depth, the steam evolved



F. G. Radcliffe, photo.

FIG. 363.—The mouth of Waimangu Geyser, N.Z.—one of the craters in the line of the Tarawera rift, opened in 1886 (fig. 328).

lifts some of the water above. Overflow takes place at the vent, and much of the lifted water still remaining in the tube, having risen to a level at which pressure is reduced, would now be at a temperature above the boiling-point, but that its temperature is instantaneously reduced by the abstraction of its surplus heat to cause the sudden ebullition of a large volume of steam. The expansion of this steam explosively ejects the water from the mouth of the tube, more of the rising water passes into steam, and the eruption continues. This goes on until the temperature of all the water is lowered below the boiling-point by admixture with the cooled water

running back into the tube. The geyser then remains inactive until the temperature rises again.

Eruption may be hastened by throwing heavy objects into the tube, thus stirring the water and causing some of it to rise, so that the pressure on it is reduced, and it boils. The introduction of soap also precipitates an eruption by increasing the viscosity of the water, which increases the size of steam-bubbles so that they cause a greater disturbance of the water, stirring and lifting it as they rise, with the result that further boiling takes place.

The Rotorua and Taupo districts of New Zealand are celebrated for their geysers. Waimangu (fig. 362), the largest geyser known, when at the height of its activity threw a large column of muddy water sometimes to a height of 1,500 ft. from a large, circular, crater-like vent (fig. 363).

Waimangu, being a new geyser, has not lined its conduit with siliceous sinter. Hence the water it ejects is muddy and dark, instead of being clear, as in the case of geysers that have been longer active.

Laccolitic Mountains.—Where sheets of intrusive rock of even thickness are intercalated between sedimentary strata they are termed *sills.* In some cases intrusive sheets, however, are not of even thickness, but swell into thick lens-shaped masses, lifting the rocks above them so as to form dome-like uplifts at the surface. Such lens-shaped intrusions are termed *laccolites.*

The up-swelling of the dome above a laccolite, of course, interrupts the cycle of erosion in progress. The dome-shaped uplifts, sometimes many thousands of feet in height, are subject to rapid dissection, and the cover of sedimentary rock may be worn off and the underlying, now solidified, igneous rock sculptured into groups of mountains. Such mountains of laccolitic origin occur in western North America.

CHAPTER XXVI.

MARINE EROSION.

Shore-line sculpture. Waves. Size of waves. Waves impelled by wind. Breaking of wave-crests in deep water. Waves running into shallow water. Breakers. Undertow. Deflection of waves. Sheltered waters. Waves as eroding agents. Transportation by currents.

Shore-line Sculpture.—The outline of the land, or form of the shore-line,* and the profile of the coast† are practically everywhere the result of the work of waves assisted by currents. Waves are energetic eroding agents, making use, as do other eroding agents, of rock-fragments as tools or abrading-material to attack and grind away solid rock; while currents are effective chiefly as transporting agents, moving waste that is stirred up by wave-action.

Waves.—Wave-motion is set up on the surface of water as a result of brushing by wind. Waves, however, travel to great distances from the region in which they originate, and so the ocean-surface is frequently found to be in motion without apparent cause; and, indeed, except in landlocked waters, the surface is never at rest. Waves within the area in which they are impelled by wind are termed *forced waves*, or "sea"; when unaccompanied by wind they are termed *free waves*, or "swell." Wave-motion consists in an orbital motion of the water-particles. In the case of free waves on the surface of deep water the orbits, or paths,

---

* The *shore-line* is the line traced by the sea-margin. As this changes its position with the tides, it is sometimes necessary in detailed descriptions to speak of the *high-water shore-line*, or *high-water mark*, and *low-water shore-line*, or *low-water mark*. The "shore" is sometimes defined as the zone over which the line of contact between land and sea migrates (Johnson, 13, p. 160).

† "Coast" is sometimes defined as the margin of the land, a zone of indeterminate width (Johnson, 13, p. 160), but in geomorphological study it is convenient to include under this head the "shore" also, and a zone of the neighbouring sea-floor, also of varying width. "Coast-line" as generally used is practically synonymous with "shore-line," but used in a regional sense, whereas "shore-line" is used when details of coastal features are referred to.

in which the particles move are closed and circular, the orbits (immediately at the surface) being all of the same size. In a wave all particles in a line at right angles to the direction in which the wave travels move together (are "in the same phase"), while successive particles in the line of propagation of the wave

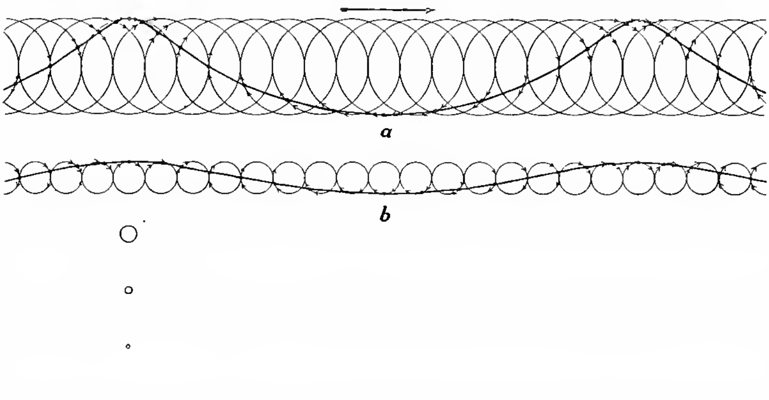


FIG. 364.—Diagrams of the orbits of a number of surface particles (or small elements) at intervals in the line of propagation of a wave, showing simultaneous positions of the particles in their orbits, and the profile of the water-surface at that instant. The large arrow shows the direction in which the waves are travelling, and the small arrows the direction of movement of the water-particles in their orbits. In *a* the height of waves relatively to the length is exaggerated; *b* represents a normal profile of ocean-waves on a natural scale; at the left side of *b* the small circles show the diminution in the size of orbits with increasing depth below the surface.

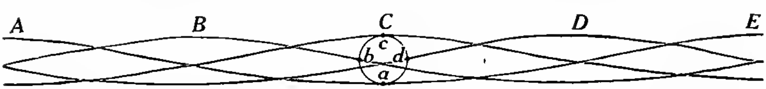


FIG. 365.—Diagram showing the movement of a particle (or small element) of water during the passage of a complete wave. The letters *a*, *b*, *c*, *d* mark the positions of the water-particle in its orbit as a wave-crest occupies the positions *A*, *B*, *C*, *D* respectively.

are (as regards their phase, or position in their orbits) a minute distance behind each other.

If the orbits of a number of superficial particles in the line of propagation of a wave be drawn in a diagram, and the position of each particle in its orbit at a given instant marked, a line drawn through the points so obtained will indicate the profile of the

undulating surface at that instant with a fair degree of accuracy (fig. 364).

If attention is confined to the movement of a single particle during the passage of a wave (fig. 365), it will be seen that, as the crest of a wave is approaching (*B*), the particle is on the side of its orbit nearer to the approaching crest, and is rising (*b*). When the crest arrives (*C*) the particle is at its highest position (*c*) and is moving forward; when the crest has passed (*D*) the particle is again on that side of its orbit nearer to the now receding crest, and is sinking (*d*); and when the wave has moved so far that the particle is at the next trough (wave-profile, *AE*) it is at its lowest position (*a*), and is moving backward to go through a similar series of motions as each succeeding wave passes. These motions are readily verified by watching the movement of a small object, such as a cork, floating on agitated water.

In the foregoing the movements of surface particles only have been taken into consideration, but it is obvious that water below the immediate surface is also affected by wave-motion. Particles a short distance below the surface are moving in orbits similar to but smaller than the orbits of those at the surface (fig. 364), and they are in the same phase as the superficial particles that are immediately above them when a crest or a trough is passing.

The source of the water which causes the upswelling of the surface in a wave becomes obvious from examination of a diagram constructed as described above, when it is remembered that the water below is moving in the same manner as that at the surface. Every particle is on the side of its orbit nearer to a crest and farther from a trough, and thus the water is heaped towards the crests, while there is a deficiency in the troughs.

Size of Waves.—The height of waves from trough to crest (*i.e.*, the diameter of the orbit of a water-particle at the surface) varies in the open ocean from about 6 ft. (low swell) to 30 ft. (heavy sea), and exceptionally even greater heights are attained. The *wave-length*, or distance from crest to crest, varies in the case of forced waves in the open ocean from 200 ft. to 500 ft., but the wave-length of a swell may be considerably greater. The *period*, or time occupied by a complete orbital movement (*i.e.*, the time that elapses between the passing of the crest of one wave and the crest of the next), is commonly between six and ten seconds. The

velocity of a wave (to be distinguished from the *orbital velocity* of a water-particle, which is much lower) may be obtained by dividing the wave-length by the period.

Waves impelled by Wind.—In waves impelled by wind the movements of the water-particles are, in a general way, similar to those in free waves, but, as the surface water has a slight forward movement (*drift*) due to the wind, particles after completing their oscillations do not return quite to the positions from which they started, and so the orbits are not quite closed and not quite circular.

The wind accelerates the movements of particles on the crests of the waves, and, as a result, the velocity of particles in the upper parts of their orbits (in which they move forward) becomes greater than in the lower parts (in which they move backward), so that the waves become asymmetrical—steeper in front than behind. The acceleration of the movements in the wave-crests by wind results also in an increase of the size of orbits, making the waves higher and higher until a limit (imposed by friction) is reached, the maximum size of waves (on a water-surface of unlimited area) depending on the velocity of the wind. As the forward movement of the waves is accelerated by the wind the wave-length also increases. Thus, under the impulsion of wind, waves, beginning as mere ripples, grow in all their dimensions until they become full-grown "seas." When the wind ceases, or the waves run out of the region in which the wind is blowing, the height is diminished owing to friction, and so the waves (now "swell") become much flattened.

Unlimited area of the water-surface is necessary for the growth of waves of really large size. It is a familiar fact that only small waves—mere ripples compared with ocean-waves—are formed in small lakes and landlocked harbours. Even in relatively large bodies of water, such as the Mediterranean Sea, waves cannot attain nearly as great a height as in the open ocean, and the same is true in those portions of the oceans near the windward shore. In the Mediterranean Sea, for example, the largest waves have a height of about 16 ft., compared with heights of 30 ft. and over commonly attained in the Southern Ocean.

Breaking of Wave-crests in Deep Water.—The formation of white caps in deep water must be distinguished from the breaking of waves where they run into shallow water (*e.g.*, on a beach). In deep water if the increase in wave-height (size of orbit) due to

the action of wind is not accompanied by a proportional increase of wave-length the result is a steepening of the waves. The crests in particular become sharpened to such an extent that they are blown over by the wind and fall forward and "break." The tendency to break is increased by the greater steepness of a wind-driven wave in front than behind. It is only exceptionally—in the greatest storms—that the largest or primary ocean-waves break in this way; but smaller, secondary waves on the flanks and especially near the crests of the larger waves rapidly attain the necessary steepness and break, forming white caps.

Waves running into Shallow Water. — Though the water to some depth is affected by wave-motion, the size of orbits decreases rapidly from the surface downward (fig. 364), being reduced to half at a depth equal to one-ninth of the wave-length, to one-fourth at a depth equal to two-ninths of the wave-length, to one-eighth at three-ninths of the wave-length, and so on until at a depth equal to the wave-length wave-motion is inappreciable. The depth at which wave-motion becomes inappreciable is termed *wave-base.**

The general account of waves given above applies to waves in water so deep that appreciable wave-motion does not extend to the bottom. As waves run into shallow water, where the depth is less than the wave-length, the water in contact with the bottom is in motion; but it is impossible for particles at the bottom to move in vertical circular orbits, and so the water there loses one component of its motion and moves back and forth in a straight line along the bottom—generally in a line that is approximately horizontal. The influence of the bottom affects also water above that immediately in contact with it, and so, a little above the bottom, particles of water are moving in orbits that instead of being circular are vertically compressed and nearly elliptical, the orbital form becoming more and more nearly normal as the surface is approached, though even at the surface the orbits are now not quite circular.

In the case of waves running in on a steep shore the linear orbits of the bottom particles are inclined instead of being horizontal, and in the extreme case of waves meeting a vertical wall the movement of the water in contact with the wall is up

* As defined by Gulliver (48), wave-base is "the depth to which maximum wave-action is possible." The term has been redefined by Fenneman, however, as the depth "at which wave-action ceases to stir the sediments" (43).

and down in a vertical line. From a vertical or very steeply inclined shore waves are reflected. Such shores are, however, very unusual, and commonly the bottom slopes gently, and the linear orbits of the bottom particles are not far from horizontal.

The friction of the bottom is distributed upward through the water, and, as the waves run into water that is shallow as compared with the wave-length, there are important changes in the wave-form. The wave-velocity is reduced, and, the period remaining the same, this diminution of velocity results in a reduction of the wave-length. A part of the energy of the waves is lost owing to the friction of the bottom; but the height of

C. A. Cotton, photo.

Fig. 366.—Swell breaking on a rocky coast, Tongue Point, Wellington, N.Z.

waves is not generally reduced owing to this cause, because there is in operation an opposite tendency towards increase in the size of orbits due to "the transmittal of the motion of a larger amount of water to a smaller amount" (Fenneman). This commonly results in an actual increase in the height of waves. Since the wave-length is decreasing and the height increasing, the waves as they run into shallower water increase in steepness.

Where waves run a long distance in very gradually shallowing water so much of the energy is absorbed by friction that the increase in height above referred to does not take place, and instead the waves are very much reduced in size before reaching the shore. This is the case on the coast of Holland.

Breakers.—The breaking of waves owing to shallowing water (fig. 366) occurs commonly in a depth about equal to the wave-height. As the waves have been advancing across shallow water all the water under each trough has been moving backward and all the water under each crest forward. The backward motion in the one case and the forward motion in the other are retarded by the friction of the bottom; but, as the depth of water under a trough is considerably less than that under a crest, the backward-moving water is retarded to a greater extent than is that moving forward. In other words, the velocity of water-particles in the upper parts of their orbits is greater than in the lower parts. The result is a steepening of wave-fronts. When now a wave runs into water with a depth about equal to the wave-height there is insufficient water in front of the wave to rise and build up the crest as the wave advances. The crest is built up to the normal form behind owing to the usual crowding of water towards it, but at the crest the normal wave-form ends abruptly. The forward motion carries the water in the crest onward so that it falls over in front of the wave, the wave breaks, and the wave-form is destroyed. Though it is the absence of water in front that is the chief cause of breaking, a contributing cause is the steepening of the wave-front that has already taken place owing to friction of the bottom.

Landward from the line of breakers on a steep beach the water surges up and down the slope, being piled up after the arrival of each breaker and receding again before the arrival of the next. When waves break far out on a very gently sloping beach or on a shoal, breaking does not quite destroy the waves, though considerably reducing their size. The reduced waves continue to roll forward to break again in shallow water. Within the breaker-line on some shelving shores each plunging crest forms a *wave of translation*, which travels across otherwise still water to the shore. (During the passage of a wave of translation water-particles move upward, forward, and downward again without a compensating backward movement.) In other cases there is a confused medley of reduced ordinary waves (waves of oscillation) and waves of translation.

Undertow.—Where waves are driven in on a coast by wind the slow landward drift of the surface water is compensated by a return current along the bottom setting away from the land. This is termed the *undertow*.

Deflection of Waves. — The crests of waves in deep water trace straight lines at right angles to the direction of propagation, which is also a straight line. As land is approached, however, those parts of a wave that first run into shallowing water are most retarded by friction. Bending of the line of the wave-crest results, the parts of the wave that are still in relatively deep water pressing on in advance of those parts that are in shallower water.

Owing to this effect a swell approaching a coast obliquely tends to swing around until the wave-crests are parallel with the shore-line, or, in other words, the waves run straight in on the beach. This has an important effect in reducing transportation of material along-shore by wave-action, for the water rushing up and down the beach inside the line of breakers travels to and fro in the same line.

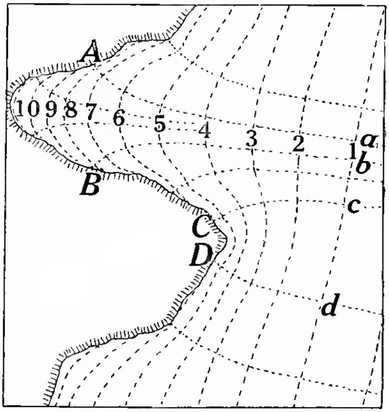


Fig. 367.—Concentration of wave-energy on headlands by refraction of waves in water of varying depth. (After Davis, modified.)

When waves are driven by wind, however, their directions are not changed to so great an extent by retardation in the sha low water. They meet the shore-line obliquely; and the water rushes up the beach obliquely, curves around, and runs back down the slope of the beach. On a very steep beach, such as the Ninety-mile Beach, Canterbury, N.Z., the along-shore movement, both of the water and of pebbles which are swept along with it may be distinctly seen not only during the landward rush but also during the return, for there the along-shore momentum is not yet exhausted when the returning water meets the uprush from the next breaking wave. The water surging up and down the beach always carries with it sand and gravel in a zigzag path along the shore-line. Thus in the littoral zone (*i.e.*, along the sea-margin, in very shallow water) some waste is transported along-shore by wave-action alone.

Another very important effect of the bending or refraction of waves in water of uneven depth is seen where waves approach an

indented coast, such as is produced by partial submergence of a dissected land-surface (p. 217 and Chapter XXVIII). Off points there is, in general, shallower water than there is off bays. Waves approaching the coast are retarded—their velocity and wave-length decreasing—to a greater extent in the shallower water lying off points than they are in the deeper water opposite bays (fig. 367). The crests of the waves are now closer together opposite points than opposite bays, and the crest-lines become more and more curved as the waves approach the shore (fig. 367, 1, 2, 3, 4, &c.). Since a wave is always propagated in a direction perpendicular to its crest-line, the lines of propagation (*e.g.*, *aA*, *bB*, *cC*, *dD*, fig. 367) bend towards the points and away from the heads of the bays. As the energy of a wave is transmitted in its direction of propagation, there is thus a great concentration of energy on the projecting points of the coast, which may be likened to the convergence of light through a convex lens (the energy of the portions of the waves between *c* and *d* being concentrated on the portion *CD* of the shore-line); and there is a corresponding spreading of the energy away from the heads of bays (the energy of the small portion of the wave *ab* being spread over the shore-line *AB*). Thus headlands are vigorously attacked by marine erosion, while comparatively smooth water is found at bay-heads, even though the bays are open to the direction from which a swell comes. As wind-driven waves are less refracted than free waves, the concentration of energy on points is less marked with storm waves than with swell (Davis, 5, pp. 491–93).

Sheltered Waters.—With the exception of the influence of varying depth of water (where the water is so shallow that friction of the bottom becomes important), there is nothing that tends to change the direction of propagation of waves. They do not turn corners—in other words, they cast "shadows," just as light does. To leeward, therefore, of a promontory or island there is smooth water, though on account of the shallowness of the water in proximity to land there is a certain amount of bending around the points, and so the "shadow" is not perfectly sharp. Land-locked harbours are thus affected by no waves except those developed within their own limits; and bays that are open on one side to the sea are protected from all ocean-waves except those that enter them directly, and even these are generally weakened, as previously shown, by deflection towards the sides.

Waves as Eroding Agents. — Since the strongest movements of the water (those resulting from wave-action) do not extend to the bottom except in shallow water, erosion takes place only around the margins of the land-masses. In the very shallow water, where waves break, the to-and-fro movement is sufficiently energetic to move large boulders, and also the impact of the waves, sometimes amounting to several tons per square foot, may be sufficient to loosen blocks of rock, and fragments are prised off owing to the suddenly increased pressure of either water or imprisoned air in crevices as a wave strikes an exposed surface of rock. Most of the erosive work of breaking waves is done, however, with the aid of rock-fragments, either derived as just described or by slumping from cliffs or supplied by neighbouring rivers. These are dashed against the solid rock, and drawn to and fro across it. The gravel of the beach is thus itself worn down and rounded, and where the layer of gravel is thin it abrades the solid rock beneath it, and undercnts slopes, causing the unsupported rock above to slip down, forming cliffs fronting the shore. The material thus supplied is worn down and disposed of by the waves, and thus the cliffs are further worn back and steepened.

As the beach-pebbles are ground down, the soft and easily decomposed minerals in them become reduced to fine mud, while the grains of hard and resistant minerals form sand, the particles of which, after being reduced to a certain minimum size, are not worn smaller, being protected from fnrther attrition by the surface tension of the films of water between them. The grains of sand thus remain somewhat angular. White sand is composed chiefly of grains of quartz, along with which there is generally a varying amount of flakes of white mica. Black sand is composed chiefly of grains of magnetite. Grey sand is a mixture of quartz-grains with magnetite or with rock-fragments not yet broken up into their separate minerals.

It is not only immediately on the shore-line that there is sufficient motion to cause erosion. As explained above, the orbital motion of the water in waves is interfered with by the bottom even at considerable depths, and converted into a to-and-fro movement. On a coast exposed to full-sized ocean-waves this movement is sufficiently strong at depths of 10 and 20 fathoms or more to move to and fro coarse sand and even gravel,* and

* Movement of gravel at a depth of 36 fathoms has been detected.

cause it to erode, or *abrade*, the bottom if bare rock is exposed. This is the process of *marine abrasion.* Though abrasion may take place at these depths, it is possible only if the layer of waste on the bottom is thin and may be all moved. If the waste is thick, then only the upper layer of it can be stirred, and no abrasion of bed-rock takes place.

The thickness of the waste-layer on the bottom, which determines whether abrasion shall or shall not take place, is governed by the supply of waste, which in turn depends on the nature of the rocks and the energy with which the waves break at the shore-line, and also to a large extent on the amount brought down by neighbouring rivers. Waste broken at the shore-line is removed in two directions—off-shore and along-shore. Removal off-shore is effected by the to-and-fro component of wave-motion, assisted by the undertow, while movement along-shore is partly due to the zigzag path followed by the swash on the beach (p. 373). Along-shore movement is also assisted by currents.

Transportation by Currents.—Ocean currents and tidal currents, though only rarely sufficiently rapid to erode even newly deposited sediment, actively transport fine silt that is held in suspension, and also coarser material such as sand and even gravel, when it is occasionally lifted clear of the bottom by wave-action.

Tidal and ocean currents flowing along a coast attain their full velocity only at some distance off-shore. In-shore they are much impeded by friction of the bottom and by irregularities of the shore-line, which their momentum does not permit them to follow. A slower current following the shore-line more closely is dragged along, however, by the off-shore current. The configuration of the coast determines whether this littoral current (as it is termed by Gilbert) shall follow the shore-line around the heads of open bays or sweep across bay-mouths from headland to headland, leaving the water of the bay still, or perhaps generating an eddy in it.

While the off-shore current can move the finer waste on the continental shelf when it is stirred by storm waves, it is the littoral current only which effects transportation of the coarser waste in theagitated water of the littoral zone. The material thus moved, together with the gravel or coarse sand swept along (as explained above) by wave-action within the breaker-line, is the *shore drift*, which is built into beaches, spits, and bars (generically *embankments*) when it reaches places favourable to accumulation (Chapter XXVIII.)

CHAPTER XXVII.

COASTAL PROFILES.

Initial coastal profiles. Steep initial profile. Sea-cliffs and the cut platform. Width of the cut platform. Profile of equilibrium. The beach. The continental shelf. Plains of marine erosion. Nearly horizontal initial profile. Progradation. Sedimentation in landlocked waters.

Initial Coastal Profiles.—The initial forms on which the marine forces — waves and currents — begin to work are very varied in profile. The cycle of marine erosion may be initiated, for example, by a movement of regional subsidence or of regional uplift, in the former case a land surface being submerged to form the new sea-floor in the shallow-water zone, and in the latter case a portion of the floor of the deeper sea being brought into this position. In place of simple vertical movement there may be warping or faulting along the new shore-line. Thus the initial coast-profile (including the portions above and below sea-level) may have any slope, from almost vertical to nearly horizontal, and may be either smooth or irregular.

Steep Initial Profile. — The initial profile is rarely so steep that waves are reflected from the shore, but where it is vertical or nearly so waves have little or no erosive effect, partly because they are reflected without breaking, and partly because there is no resting-place for loose material at a convenient depth to allow it to be picked up and used by waves as tools, or weapons, in their attack on solid rock at the shore-line. Such material as is dislodged by the impact of waves on the initial shore slips immediately into deep water.

When, however, a slope initially too steep to cause waves to break has had its steepness reduced by slumping and subaerial erosion accompanied by accumulation of talus at the base (fig. 368, *b* and *b′*), waves will no longer be reflected, but will break, and will dislodge by their impact weathered and joint-

bounded blocks of unweathered rock. This takes place also without any delay on shores which, though steep, have yet sufficiently gentle slopes initially to cause waves to break upon them.

Waves encountering a steep shore have lost but little energy owing to friction of the bottom before they reach the shore-line. They expend their energy at the breaker-line. Most of this energy, moreover, is available for the attack on the land, comparatively little being used up in grinding waste, for a steep coast is not encumbered with waste. Sufficient is present to act as tools with which the rushing and swirling water may batter and rasp the shore, but the bulk of the broken material is quickly drawn out into deep water and deposited there. Under these conditions wave-action has its maximum efficiency as a destructive agency, and the shore-line recedes as a line of sea-cliffs of increasing height.

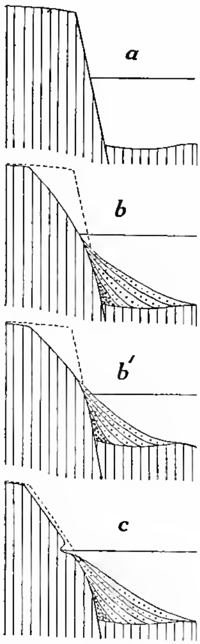


FIG. 368. — To illustrate the beginning of wave-attack on a very steep initial coast. *a*, initial form; *b*, *b′*, forms after the profile is rendered less steep by accummulation of talus; *c*, sequential form, showing the beginning of wave-work.

Sea-cliffs and the Cut Platform.—Erosion may be so rapid that in cliffs of tough, unjointed rock a *nip* is cut—that is, a notch along the base, above which the cliff overhangs (figs. 368, *c*; 369). The material above slips down, however, before long, and the cliffs recede as the fallen blocks are themselves attacked by the waves, broken up, and removed, and the attack on the cliff-base continues.

At this early stage in the development of the wave-cut profile, at which the shore-line is still rapidly receding, the steepness of any cliff depends largely on its structure. Cliffs of tough rock may be vertical or may overhang a nip, or, if a system of division-planes — stratification or joints — dipping inland is the only one present, they may slant outward for their full height.

The retreat of young and steep cliffs takes place as a succession of rock-falls and landslips, the latter being particularly large where resistant strata overlie more easily eroded formations which crop out along the shore (fig. 370).

At the foot of a line of receding sea-cliffs there is a gently-sloping wave-cut platform (fig. 371). The cliff-base is generally at

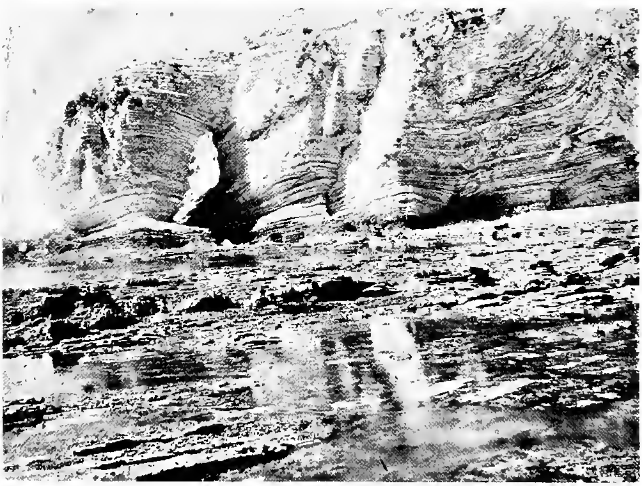
F. G. Radcliffe, photo.

FIG. 369.—Nip in cliffs of tough cemented rock composed of fragmentary volcanic ejectamenta (breccia), Whangaroa, N.Z.

high-water level, for the material above that level is to some extent loosened by subaerial weathering, and thus prepared for ready removal even by weak waves (p. 29 and fig. 26). Exceptionally, however, where a steep coast is subject to very violent wave-attack, the cliff-base is below high-water level and the landward

C. A. Cotton, photo.

FIG. 370.—Coastal landslip at Amuri Bluff, Marlborough, N.Z.



P. Marshall, photo.

FIG. 371.—Sea-cliff and wave-cut platform at Amuri Bluff, N.Z.

edge of the wave-cut platform is covered at high water to a depth of several feet.* In such a case subaerial weathering is unable to keep pace with marine erosion.

Farther out, at the line of breakers, where waves expend the greater part of their energy, there is sufficient movement of the water to keep very coarse waste in motion. This material—boulders, gravel, or coarse sand—is dragged to and fro over the bottom, unless the supply of waste is excessive, when only the upper layers of waste will be moved and ground. The abrasive action

C. A. Cotton, photo.

Fig. 372.—Terrace formed by a remnant of an uplifted wave-cut platform, west of Tongue Point, Wellington, N.Z.

of the coarse waste is such that a bottom of solid unweathered rock may be rapidly worn down. Seaward also to a considerable depth wave-motion drags finer waste to and fro, and abrasion continues on such parts of the bottom as are occasionally swept clear of a protective layer of waste. This continued deepening off-shore by the process of marine abrasion accounts for the fact

* Twelve feet in the case of some headlands at Samoa, according to R. A. Daly (*Geol. Mag.*, vol. 57, p. 249, 1920).

that the cut platform usually slopes seaward from the base of the cliffs. The seaward portion of the cut platform has been longer subject to wave-action than that at the base of the cliff, and so has been more deeply abraded. The wearing-down of the outer part from sea-level has taken a long time, but erosion will go on as long as the waste on the bottom continues to be moved to and fro over bare rock.

If raised above sea-level the cut platform is termed a *plain of marine erosion.* Remnants of such uplifted platforms, cliffed at the margin as a result of renewed marine erosion following the uplift, form terraces bordering various parts of the coast-line of New Zealand. They are conspicuous along the southern coast of the North Island, in the vicinity of Wellington (figs. 372, 373).

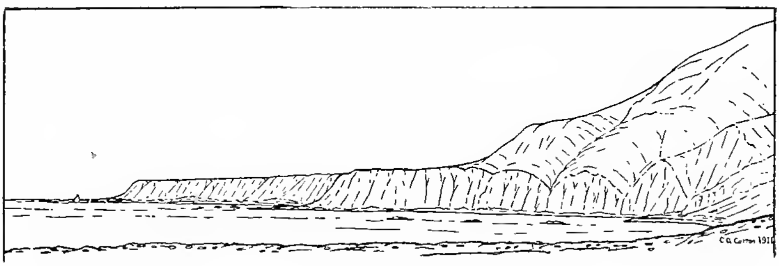


FIG. 373. — Remnant of an uplifted wave-cut platform, Tongue Point, Wellington, N.Z., cliffed by marine erosion in the current cycle, showing the graded off-shore profile of the former cycle.

Width of the Cut Platform.—The waste resulting from marine erosion, together with that brought down to the sea by rivers, is moved about in various directions on the bottom by the to-and-fro movement of the agitated water and by chance currents, some of it becoming very finely comminuted in the process, but, as the undertow gives the bottom water a preponderating seaward movement, the waste is worked slowly outward. Though the upper layer of this comminuted waste is in motion, there is generally a sufficiently thick accumulation of it on bottoms considerably shallower than the depth of wave-base to protect the bed-rock floor from abrasion. The cut platform does not then extend out to the level of wave-base, but is flanked seaward by a bank of sediment consisting in its deeper parts of waste that has travelled out into

water too deep to be stirred to the bottom by wave-action—*i.e.*, deeper than wave-base—and has come to rest there, and in its upper part of sediment above wave-base, the upper layer of which is subject to movement and is in process of transportation. This bank of sediment forms the *built platform.* The equilibrium of the sediment forming that part of the built platform above wave-base depends on a continuance of the supply of waste, for, if the supply were to be cut off, transportation due to movement of the bottom water would continue, the sediment lying above wave-base would thus be gradually removed, and if bed-rock were exposed by the stripping-away of the sediment it would be subject to abrasion as long as any fragments large enough to act as tools remained upon it. The depth at which the cut platform ends and the built platform begins thus depends on equilibrium between waste-supply and transportation.

Profile of Equilibrium.—At an early stage in the erosion of a steep coast, after a certain amount of cliff- and platform-cutting has taken place landward and has been accompanied by sedimentation farther seaward, the slope from the shore-line to the outer edge of the platform formed by this cutting and building becomes smooth and nearly uniform, there being a state of balance between erosion and deposition at all points on it. The profile is now *graded* (Davis, 4, p. 701), or a *profile of equilibrium* has been developed (Fenneman, 41). This profile is slightly concave, being steepest near the shore-line. The profile shown in fig. 26 has not yet attained the graded condition, as there is an abrupt drop at the outer edge of the cut platform, which in this case is above low-water level.

The Beach.—Along such parts of a coast as are not at present being actively cut back—more especially opposite bays, but frequently also, as a temporary condition, in front of cliffs the form of which shows that they were recently attacked at the base—the bottom may be covered with a continuous or nearly continuous sheet of waste, the graded profile of the surface of which is continued above high-water level, where sand or gravel has been piled up by the breaking waves. Between tide-marks the surface of this waste sheet is the *beach,* while the portion above high-water level may be piled into the form of a regular ridge—the *beach-ridge,* or *storm beach.* The beach and beach-ridge are not permanent accumulations,

but are liable to be rapidly cut away by wave-action in response to some changed condition of weather or currents.

The Continental Shelf.—The off-shore profile, once graded, remains so unless the cycle of marine erosion is interrupted by earth-movements; but the width and slope of the whole platform (or *continental shelf*) may vary widely. As long as wave-action remains vigorous and waste is removed the shore-line retreats, and at the same time the built portion of the platform grows seaward as additional waste is deposited. The outer margin of the platform remains at the depth of wave-base (a depth of 70 to 100 fathoms off exposed coasts), for sediment sliding over the edge of the existing shelf or settling from suspension accumulates in the still water up to this level. Thus, the shelf increasing in width and

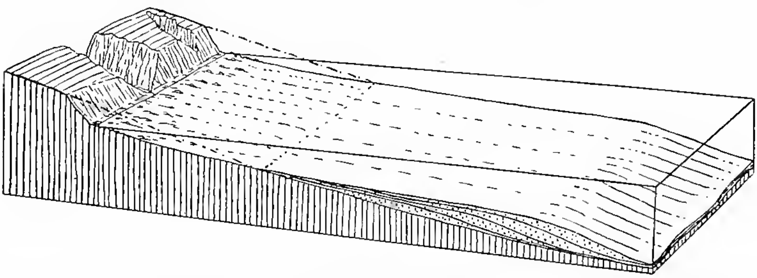


FIG. 374.—Diagram of cut and built platforms, together forming a continental shelf. In the front of the diagram several earlier profiles of the built platform are shown. The broken lines from the cliff-top to the edge of the cut platform indicate the initial profile of the coast.

its edge remaining at the same depth below sea-level, the slope of its surface becomes more and more gentle (fig. 374).

The shelf surrounding New Zealand has a width in most parts of between ten and fifty miles. In a few places, however—at several points along the south coast of the North Island, for example—it narrows to a width of only two or three miles. At Cape Turakirae, where the shelf is narrowest, very recent uplift has exposed a strip of it, varying in width up to 400 yards (figs. 375, 376), which forms an exceptionally steep coastal plain. The exposed shelf in this case consists in part of bed-rock, forming prominent stacks, but there is a discontinuous veneer of boulders, some of them enormously large, the coarseness of the waste corresponding to the exceptional steepness of the profile, which allowed the sea to abrade the cut

platform and attack the cliffs behind the former shore-line with the energy of the ocean-waves practically undiminished by friction of the bottom. Two prominent ridges, or raised storm beaches, of smaller boulders and gravel (in addition to that at the rear of the whole plain) mark positions of the sea-margin during pauses in the uplift (fig. 376), and the "boulder plain" is also partly covered by alluvial fans (Aston, 24).

The sediment on the surface of a normal, gently inclined shelf is principally fine sand, passing into coarser sand, and in some cases gravel, as the beach is approached, and into muddy sand or sandy mud towards the outer edge.

C. A. Cotton, photo.

Fig. 375.—Steep coastal plain exposed owing to uplift of a steep continental shelf consisting of a cut platform with a veneer of boulders, Cape Turakirae, Wellington, N.Z.

Beyond the edge of the shelf there is a steeper slope (the *continental slope*) leading down into the ocean depths. This is the front of the accumulating bank of sediment forming the built platform. As it is of the same nature as the steep front of a delta, it may also be called the *fore-set* slope. The subaqueous portions of the deltas of large rivers are, indeed, merely salients of the continental shelf. The material on this slope, and also that underlying the coarser material on the top of a shelf built out while sea-level remains stationary, is principally mud that has settled down and come to rest in the still water below wave-base. Accumulation of

this fine material cannot take place where there is any motion of the bottom water.

The hard parts of marine organisms, principally shells, are entombed with the sediments as *fossils*, and where the supply of waste from the land almost fails, or marine life is particularly abundant, the remains of organisms, sometimes ground to fragments by mutual abrasion, accumulate either on the surface of the shelf or on the continental shelf as calcareous deposits, which form beds of limestone when consolidated.

C. A. Cotton, photo.

Fig. 376.—View across the steep coastal plain of Cape Turakirae at its widest part, showing the enormous boulders and stacks surmounting the uplifted cut platform The ancient sea-margin is at the base of the slope in the foreground, and farther out two gravel ridges mark successive positions of the shore-line.

In warm seas calcareous deposits accumulate in very shallow water as *coral reefs*, which consist of the remains of a great variety of lime-secreting organisms (including plants), but are strengthened and bound together by massive and tree-like "reef-building corals." These coral growths, which are the skeletons of clustered and branching colonies of attached animals (polyps), budding and branching from one another, but individually resembling the soft-bodied sea-anemones seen in rock-pools, can live only in clear salt water

the temperature of which does not fall below 68° F., and at depths not exceeding 20 or 30 fathoms.

When a coral reef becomes established along a shore (a *fringing reef*) it affords complete protection from further marine erosion (fig. 377).

The continuity of a fringing reef is broken by passages (fig. 377) opposite the mouths of streams, the sediment from which stunts the coral or completely prevents its growth. A *barrier reef* differs from

S. Taylor, photo.

FIG. 377.—Fringing reef, Atiu, Cook Islands, protecting a steep shore from marine erosion.

a fringing reef in that it is separated from the land by a strip of fairly deep water (see Chapter XXVIII).

Coral reefs are bordered seaward by graded shelves, sometimes very steep, built of fragments of coral rock broken by wave-action.

Plains of Marine Erosion.—Since the slope of the continental shelf becomes more and more gentle as its width increases, the waves running shoreward across it are affected more and more by the friction of the bottom, and so reach the shore-line with diminishing

energy. Retreat of the shore-line becomes slower and slower. The wave-cut cliffs, at first nearly vertical, later assume more and more gentle slopes as the subaerial processes grading the slopes are able to keep pace with the slower retreat of the cliff-bases. At last wave-energy will become so reduced that it will be almost completely used up in grinding and transporting seaward the waste brought down by streams. The rate of retreat of the shore-line thus falls off rapidly, and in the case of land with strong relief it will become so slow as to be negligible, until the relief of the land has been destroyed by subaerial erosion, when the supply of waste falls off and even much-enfeebled waves can attack the shore-line and abrade the cut platform. Thus marine planation seems capable ultimately of cutting a platform of unlimited width—*i.e.*, of cutting the land away altogether,* but the process demands an extremely long period of still-stand.

During progressive submergence, on the other hand, there is no retardation of the rate of marine planation by increase in the width of a shallow-water zone. As the land and continental shelf sink relatively to sea-level, the depth of water over the cut platform constantly increases, thus allowing the waves always to reach the shore-line with sufficient energy to erode vigorously, and so to extend the cut platform landward (Ramsay; also Richthofen, 19, p. 354). Such a cut platform, unlike that formed while sea-level is stationary, does not owe its seaward slope to continued abrasion of the bottom in the moderately deep water off-shore, but to continued submergence of the successive strips cut down to the level of the line of breakers at the shore-line. The plain so formed is generally buried beneath sediment progressively as it is cut.

Among the broad areas in various parts of the world which are shown by the survival of plateau-remnants to be erosion surfaces of little or no relief uplifted and dissected, though some are certainly peneplains, others appear to be plains of marine erosion; and this is certainly the case with large areas of fossil plain on which marine covering beds still lie. Considerable portions of the stripped fossil plain now forming conspicuous plateau features in New Zealand (Chapter XI), notably in northern Nelson, were cut by marine erosion, for the remnants of cover surviving here

* Johnson, 13, pp. 234–38.

and there on the surface consist of marine deposits and have a layer of beach-worn pebbles or boulders at the base, which lies on a smoothly abraded surface of unweathered rock.

Deformed structure of the rocks underlying a fossil plain often indicates that the region was once mountainous, and therefore that a vast amount of erosion was necessary to destroy its relief; but it is not necessary to assume that the whole of the planation was the work of the sea. The amount of waste that would have to be removed during the levelling-down of a mountainous land is enormous, and the movement of subsidence that must be postulated to explain the formation of an even plain by marine erosion from such an initial form is extremely slow and must go on evenly and continuously throughout a vast lapse of time. It is more probable therefore, that only regions of small relief—that is, regions that have already been reduced by subaerial erosion to peneplains—have been completely planed off by the sea over wide areas The soil on the low salients of a peneplain is deeply weathered and will offer little resistance to marine erosion. So planation of such a previously prepared surface might be effected by the sea during a movement of subsidence occupying a comparatively short time.

Nearly Horizontal Initial Profile.—All the foregoing statements refer to a coast where the initial profile is so steep that erosion landward and deposition seaward are necessary in order to develop a graded profile. The initial profile may, on the other hand, be less steep than a profile of equilibrium, for the development of which erosion will be necessary seaward and deposition landward. Such an initial profile may be formed by simple uplift, which causes the shore-line to take a position far out on the former continental shelf. If strong erosion of the bottom takes place at, and seaward of, the breaker-line, the sand thus stirred up is thrown up either on the beach or seaward of it, forming in the latter case an emergent ridge, termed an *off-shore bar,* or *barrier,* between which and the initial shore a lagoon is enclosed.

An off-shore bar generally grows in width by the addition of successive strips, and the dried sand on it is piled up into dunes by the wind. The shallow lagoon within remains connected with the sea by a few channels kept open by rivers and by tidal currents. It becomes nearly filled with fine sediment and salt-marsh vegetation, which forms a layer of peat, and over this the sand-dunes

may extend landward. The whole south-eastern coast of the United States is fringed by off-shore bars bordering a very gently sloping coastal plain.

C. A. Cotton, photo.

FIG. 378.—General view of the narrow southern end of the prograded coastal lowland of western Wellington, N.Z., backed by wave-cut cliffs. From the Wellington–Paekakariki Road.

Typical off-shore bars built as a consequence of recent emergence are not known in New Zealand with certainty. The low sandy strips of land along the coast of the Bay of Plenty, which enclose

the harbours of Katikati and Tauranga and extensive areas of low-lying swamp farther east, may perhaps have originated in part as off-shore bars; but some parts of them have every appearance of having grown lengthwise along-shore as spits (Chapter XXVIII) while intervening projections of this coast of submergence were being cut back by marine erosion. If the sandy strips originated partly as off-shore bars it was not necessarily uplift in this case that caused the shallowing of the sea leading to their upbuilding, for considerable shallowing must have occurred from time to time when the

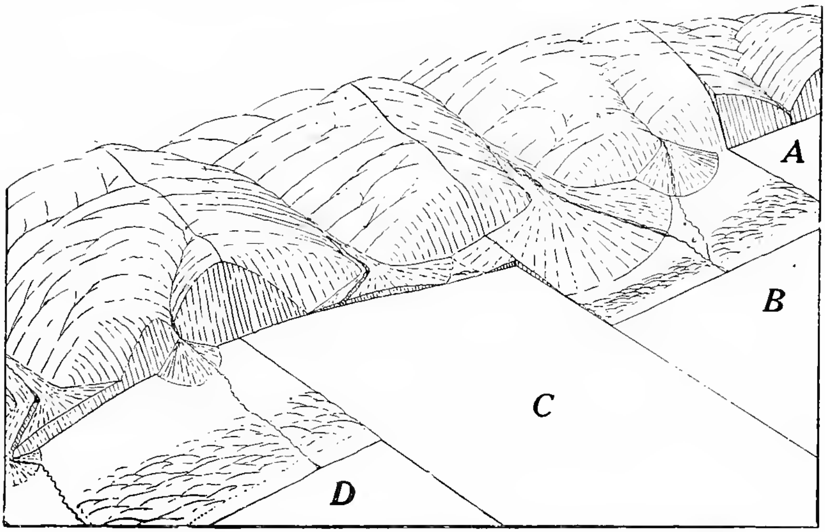


Fig. 379.—Diagram of successive stages of a coast alternately retrograded and prograded.

showers of volcanic "ash" fell which have very recently added layer after layer to the surface of the neighbouring land.

Progradation.—Where the initial profile, though steeper than in the case where an off-shore bar is built, is yet not steep enough near the shore to be a profile of equilibrium under the existing conditions of waste-supply, sand or gravel is thrown up by the breaking waves at the shore-line, which advances seaward as successive new beach-ridges are added to it. This process is termed *progradation* (as contrasted with *retrogradation*, the cutting-back of

a coast by marine erosion), and the coast is said to be *prograded*. In this way a *foreland* is built, or, if it is continuous for some distance along-shore, a *strand-plain*. If the material thrown up is gravel the successive beach-ridges are distinguishable in profile, but if it is sand these are destroyed by wind, and dunes are built. Parallel dune-ridges, fixed by vegetation, may indicate successive positions of the shore-line (fig. 260).

Progradation is not confined to young coasts where the first grading of the profile is still in progress. It takes place wherever

C. A. Cotton, photo.

FIG. 380.—Fan with cliffed seaward margin, a short distance north of Paekakariki, coastal lowland of western Wellington, N.Z. (see also fig. 381).

rivers supply a greater quantity of waste than can be drawn seaward or transported along-shore by waves and currents, or where excess of waste supplied by along-shore transportation (Chapter XXVI) is piled up owing to the presence of some obstacle barring its farther progress.

In New Zealand progradation is going on along the Ninety-mile Beach of Canterbury (fig. 401). The material here is coarse gravel, which is brought down in vast quantities by the rivers crossing the Canterbury Plain. The dune-covered seaward portion of the

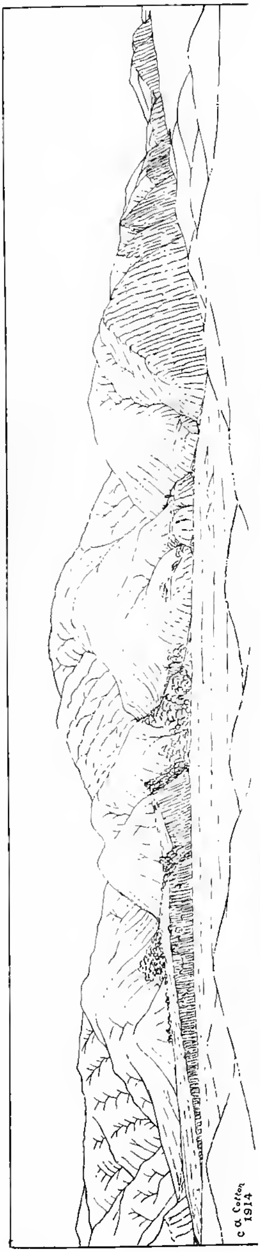


Fig. 381.—The Paekakariki coast, N.Z., viewed from the fixed dunes on the modern foreland.

coastal lowland of western Wellington also owes its origin to the large volume of sand brought down by the rivers to the northward (fig. 378).

A peculiarity of this prograded lowland is that it includes features developed during alternating phases of progradation and retrogradation, which are well displayed near the southern end, in the neighbourhood of Paekakariki (fig. 379). The material composing the foreland is of two kinds, gravel of local origin and sand which has been transported along-shore from the north. The abundance of the latter at certain times may be regarded as the cause of progradation, and reversals of the process appear to have resulted from fluctuation in the supply. The sand thrown up by the sea in the first traceable progradational phase apparently formed a foreland, on which the gravel supplied by local streams accumulated as fans (fig. 379, *B*). Then came a phase of retrogradation, in which the narrow southern end of the foreland was almost completely cut away, *C*. A later extensive progradation has built a new dune-covered foreland several miles in width, *D*. The cliffs of the earlier retrogradational phase are now somewhat subdued and rounded, and pass by a smooth concave curve at the base into the talus slopes and fans of the next phase — progradation. These fans are irregularly truncated by the cliffs developed in the later retrogradational phase, which are cut back far enough in places to intersect the line of cliffs of the earlier retrogradation, *D* (see also

figs. 380, 381). In front of the newer line of cliffs lies the modern foreland, consisting of a belt of dunes, which on the landward side are fixed by vegetation, and a narrow strip of marshy plain between the fixed dunes and the cliffs (figs. 380, 381).

Sedimentation in Landlocked Waters. — In sheltered waters (*i.e.*, small lakes or enclosed bays) wave-base is at a shallow depth —perhaps 4 or 5 fathoms, but varying with the size of the sheet of water and the length of the waves which arise on its surface. Sediment sinking below wave-base is undisturbed except by strong tidal currents, which scour out and keep open channels through it. The waste carried by streams into landlocked embayments and broken by wave-action around their margins is deposited in them, therefore, and little makes its way out to sea until the embayments are filled up nearly to sea-level. Indeed, the fact that such bays are generally so filled, though the stage of the shore-line cycle may indicate that the date of their formation by submergence of the land-surface (Chapter XXVIII) was very recent, and the observed rapidity with which silt accumulates in sheltered waters, indicate that the tide carries into the initial embayments and deposits there a great quantity of fine waste from the outer coast (13, p. 113).

CHAPTER XXVIII.

COASTAL OUTLINES.

The shore-line cycle. Initial forms of coasts. Coasts of submergence and of emergence. Classification of coasts. Depressed coasts, or coasts of submergence. Development of minor irregularities. Simplification of the coastal outline. Spits and bars. Maturity. Barrier (coral) reefs and atolls associated with coasts of submergence.

The Shore-line Cycle.—In the development of coastal features marine erosion plays a part analogous to that normally assumed on the surface of the land by rain and running water in producing those sequential forms which supply all the detail in a general view of either a coast or a landscape. When a broad view of a coast is taken, however, it is generally possible to distinguish more or less distinct traces of larger initial forms, as is the case also in many landscapes. Actual coasts are sequential forms developed by erosion, and in part by accumulation, from varied initial forms. A succession of stages, or *shore-line cycle*, through which the coastal features normally pass, can be developed for each kind of initial coast.

Initial Forms of Coasts.—There is a strong contrast between coasts of submergence and coasts of emergence in the early stages of the shore-line cycle (fig. 382). The latter, bordering areas of newly exposed sea-floor, are straight and featureless, while the former, on account of the *drowning*, or partial submergence, of the features of a diversified land-surface, may be highly irregular.*

A striking object-lesson of the effects of partial submergence of a mountainous land is sometimes afforded by the view from above of fog-banks lying in valleys and reproducing the outlines of branching and winding bays with great fidelity (fig. 383).

* The fact that partial submergence of a deeply dissected land will give a deeply embayed shore-line was first noted by J. D. Dana, at the Island of Tahiti, which he visited as a member of the Wilkes exploring expedition.

Besides initial forms due to general submergence and emergence there are fault coasts, initially fault-scarps descending to the sea; while another type of initial coast results from accumulation of volcanic material, where a growing volcano forms a salient of the coastal outline, or is built up from the sea-bottom to become an island; and yet another distinct type is that found where the sea has entered troughs excavated by glaciers extending below sea-level.

Coasts of Submergence and of Emergence.—Movements of the ocean-level ("eustatic" movements) will produce results similar to uplift and subsidence of the land except that the eustatic

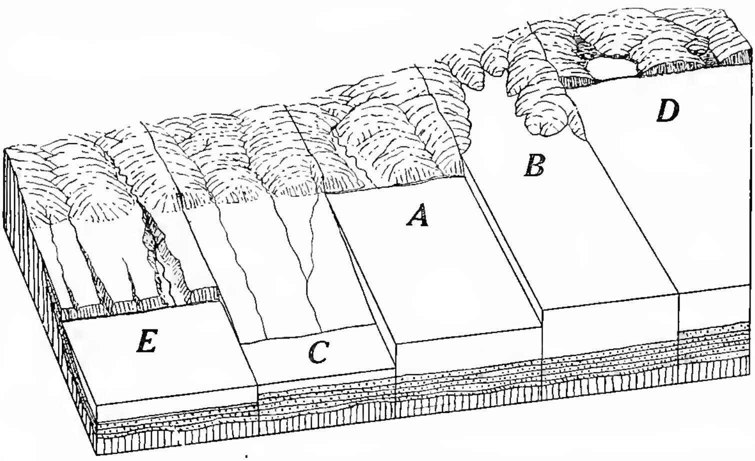


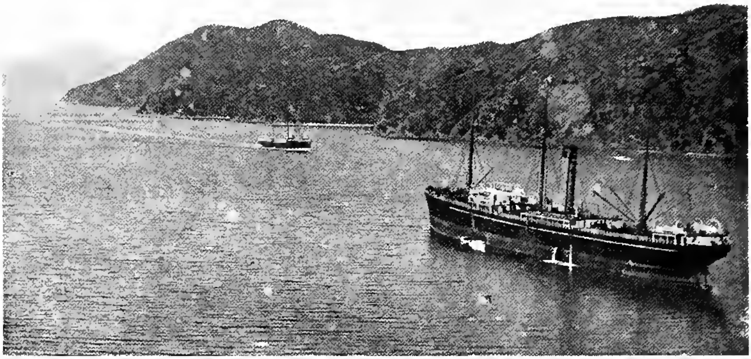
FIG. 382.—Coasts of submergence and of emergence (represented in the diagram as though due to fall and rise of sea-level. *B*, effect of submergence, or subsidence, and *C*, effect of emergence, or uplift; *A*, pre-existing coast; *D* and *E*, sequential forms derived from the initial forms *B* and *C* respectively.

movements will be world-wide and their effects of equal magnitude over large areas, whereas the amount of submergence or emergence often varies from point to point, and there is sometimes a rapid passage from a coast of submergence to one of emergence, indicating that movement of the land—often diverse movement—has been responsible for the majority of initial coasts.

Coasts due to warping need not be considered separately, for there is no essential difference in form between shore-lines due to regional depression or uplift and those in which the submergence

C. L. Adkin, photo.

FIG. 383.—The upper Mangahao Valley, Tararua Range, N.Z., partially filled with fog, illustrating the deeply embayed coastal outline that would result from partial submergence of this mountain-range.



F. G. Radcliffe, photo.

FIG. 384.—Branching bays formed by the drowning of ravines tributary to the larger valley which has been submerged to form a ria, Queen Charlotte Sound, Marlborough, N.Z. Since submergence low cliffs have been developed by the small waves arising on the landlocked waters of the sound.

M. T. Cotton, photo.

FIG. 385.—Drowned valleys of a dismembered river-system, Bay of Islands, N.Z.

or emergence is local and due to gentle tilting or warping. The actual tilting or warping movement may involve uplift inland and depression seaward, and yet at the shore-line may result in either submergence or emergence, according as the hinge-line, or axis, of the warping or tilting is landward or seaward of the pre-existing shore-line.

Classification of Coasts.—An exhaustive classification of coasts would include an enormous number of types, for the possibilities of variation are infinite when such variables as the structure of the land and its relief and the successive stages of the shore-line cycle are taken into account. Failing a complete classification, however, which would not lend itself to compact tabular statement, the following synoptic scheme serves to bring together coasts related either in their initial or sequential forms.

- I. Initial coasts resulting from volcanic accumulation
- II. Initial coasts resulting from either regional movement or marginal warping
  - A. Coasts of emergence (movement at shore-line is uplift)
  - B. Coasts of submergence (movement at shore-line is depression)
- III. Initial coasts resulting from faulting
  - A. Afterwards uplifted
  - B. Afterwards depressed
- IV. Initial coasts resulting from glacial erosion below sea-level

All of the above are then divided into:

- (1) Retrograded
- (2) Prograded
  - (*a*) By alluviation
  - (*b*) By wave-action

Depressed Coasts, or Coasts of Submergence.—Most deeply embayed coasts have been recently submerged. Submergence of the seaward margin of a dissected land-surface allows the sea to enter the lower parts of valleys, converting them into *drowned valleys* (fig. 382, *B*). The rivers are *betrunked**—*i.e.*, shorn of their

* Contrast with "beheading," which deprives rivers of their headwaters.

D. J. Allersley, photo.

FIG. 386.—Initial form of shore-line due to submergence, scarcely modified by erosion, Elaine Bay, Pelorus Sound, N.Z. The islands are partially submerged hills.

F. G. Radcliffe, photo.

FIG. 387.—Islands resulting from "drowning" of topography within an embayment of the young depressed coast of North Auckland, Whangarei Heads, N.Z.

lower courses—and the river-systems are *dismembered*—*i.e.*, streams formerly tributaries of trunk rivers now enter the sea by separate mouths (figs. 384, 385). It is by the drowning of valleys that estuaries and a great many of the most useful harbours of the world have been formed.

Where before submergence the rivers run more or less parallel to the coast in open valleys (as where the strike of strata, folds, or blocks is parallel to the coast), and reach the sea by way of transverse gorges, very fine landlocked harbours may be produced by drowning. Where, on the other hand, the strike of structures is transverse to the coast, drowned valleys extending far inland and broadening at the mouth are formed. These are termed *rias*.

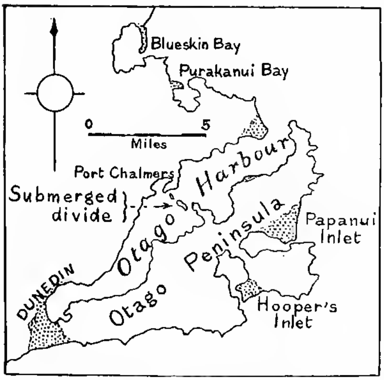


FIG. 388.—Map of Otago Harbour and Peninsula, N.Z., showing drowned valleys, spits, bay-bars, and a submerged divide.

Excellent examples of rias are afforded by Queen Charlotte and Pelorus Sounds and the associated smaller inlets in Marlborough, N.Z. (figs. 384, 386).

Partially drowned ridges form projecting capes, headlands, and outlying islands, while islands are formed also within the embayments by the unsubmerged higher parts of spurs (figs. 386, 387). Occasionally divides are submerged, and large islands are separated from the mainland by straits resulting from the drowning of two or more neighbouring valleys. In New Zealand Kawau Island and D'Urville Island are examples. Otago Peninsula was an island formed thus by the submergence of a divide (Marshall, 58) (figs. 388, 389), though it has been again joined to the mainland at another place by an isthmus of sand (Chapter XXIX).

Development of Minor Irregularities.—The initial off-shore profiles along a coast of submergence are irregular, and are, in general, much steeper than a profile of equilibrium. Thus erosion begins at once along the shore-line, outstanding points being attacked by ocean-waves, and the shores of enclosed and sheltered

F. G. Radcliffe, photo.

FIG. 389.—The submerged divide near Port Chalmers, in Otago Harbour, N.Z. In the background is Otago Peninsula.

C. A. Cotton photo.

FIG. 390.—Sea-cliff and rock platform near Porirua, N.Z., showing minor irregularities etched out by wave-action, including a shallow cave in an anticlinal structure of the rock.

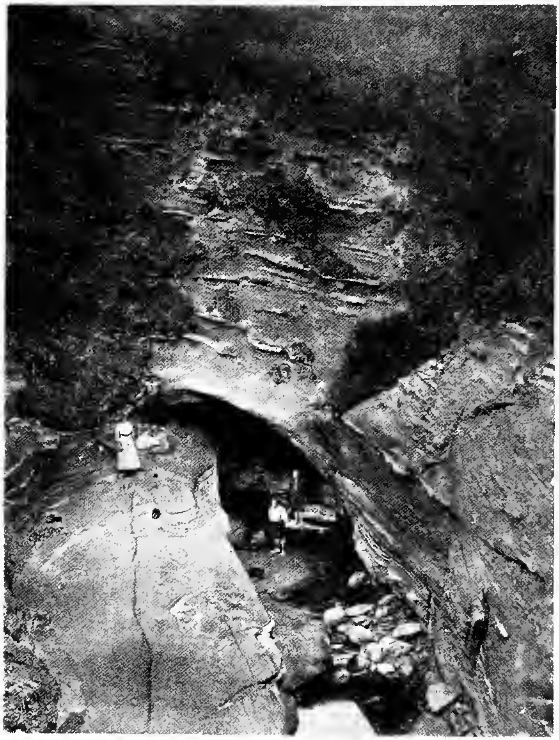
C. A. Cotton, photo.

FIG. 391.—Small irregularities produced by marine erosion acting on a young submerged coast ("crenulate" stage), Bay of Islands, N.Z.

F. G. Radcliffe, photo.

FIG. 392.—Sea-cave forming a tunnel through a narrow promontory, Whangaroa, N.Z. The rock above the tunnel is noticeably different from that at either side.

waters by the smaller waves that arise within their own limits. The initial outline, though it may trace an intricate pattern, is made up of smooth curves determined by the intersection of the plane of sea-level with the graded subaerial slopes, and the first effect of wave-attack on the outline is to introduce innumerable



F. A. Hargreaves, photo.

Fig. 393.—Blowhole, Pourewa Island, near Tolaga Bay, N.Z.

minor irregularities (such as those shown in figs. 390, 391), determined by differences of rock-hardness and the presence of joints and any other weak places. A young depressed coast at the sequential stage at which these small irregularities have made their appearance is described by Johnson as *crenulate* (13, p. 278).

Steeply inclined sheets of shattered or easily weathered rock—whether strata or dykes—outcropping at the shore-line are excavated to form sea-caves along the cliff-base (figs. 390, 392) or open clefts in the cliffs and rock platforms (fig. 390). A *blowhole* is formed where part of the roof of a deeply-penetrating sea-cave falls in, leaving an open funnel, up through which a blast of air and spray is projected as each wave enters the mouth of the cave. There is a well-known blowhole on Otago Peninsula, and another

F. G. Radcliffe, photo.

Fig. 394.—Dyke projecting as a result of differential erosion beyond the general line of a young submerged coast, the "natural wharf," Whangarei Heads, N.Z.

near Manukau Heads, Auckland. One such (fig. 393), on Pourewa Island, near Tolaga Bay, N.Z., is connected with the sea-cliff by a tunnel 200 yards in length.*

The outcrops of strata or dykes of relatively resistant rock may remain projecting prominently beyond the general line of the shore (fig. 394).

* J. Henderson and M. Ongley, 60, No. 21, p. 22.

F. G. Radcliffe, photo.

Fig. 395.—Stacks and "almost stacks" at Cape Kidnappers, N.Z. Further enlargement of the clefts and sea-caves at the cliff-base will result in the separation of successive pinnacles of the cape as stacks.

C. A. Cotton, photo.

Fig. 396.—A slightly uplifted cut platform with a number of unconsumed stacks, Miramar Peninsula, Wellington, N.Z.

Masses of rock that are resistant to erosion because relatively free from joints may remain standing above the cut platform beyond the receding line of cliffs as steep-walled *stacks* (figs. 395, 396), and some of these may remain connected to the cliffs by arches (fig. 371). Outlying stacks when worn down to sea-level become *reefs*.

Even within the sheltered embayments formed by the extensive drowning of branching river-systems, such, for example, as those forming the numerous harbours around the coasts of the Auckland Province, the waters of which are quite landlocked and thus free

F. G. Radcliffe, photo.

Fig. 397.—Whangaroa Harbour, a drowned valley-system, showing cliffing due to wave-action.

from disturbance by ocean-waves, sea-cliffs are cut, and the initial outlines are greatly modified by the action of the small waves arising within the limits of the embayments (figs. 397–399). In some cases—*e.g.*, Auckland Harbour—the coastal rocks are weak and thus easily eroded (fig. 398); while in other cases—*e.g.*, Bay of Islands (fig. 26)—rapid subaerial weathering prepares waste for erosion even by feeble waves.

Simplification of the Coastal Outline.—Though marine erosion etches out small irregularities on rocky shores, yet its general effect on the initially intricate outline of a submerged coast is to

simplify it by cutting back projecting headlands (figs. 400, 401), and also outlying islands, upon which wave-energy is largely concentrated by the refraction of waves (p. 374). Convincing evidence that the land has been cut back a considerable distance is often found in an inland slope of the land-surface from the edge of the sea-cliff—so that further recession will reduce the height of the cliff. This indicates that a hill has been more than half cut away (fig. 437, centre).

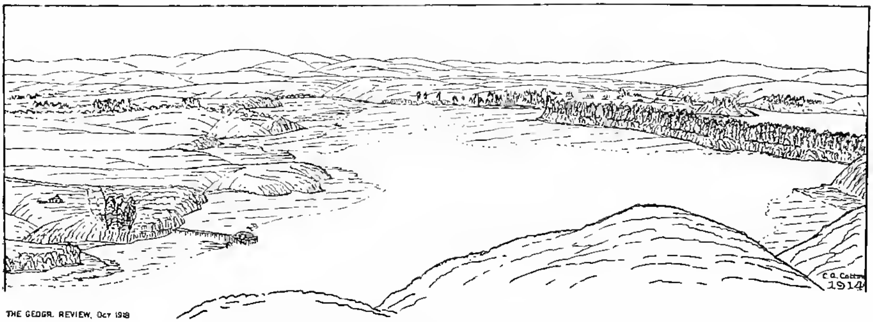


FIG. 398.—The upper reaches of Waitemata Harbour, Auckland, N.Z., showing extensive cliffing along the sea-margin.

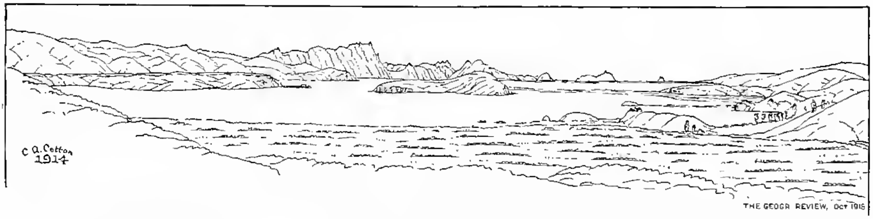


FIG. 399.—Whangarei Harbour, N.Z., showing cliff-development along the sea-margin, and also extensive progradation (p. 391) further modifying the initial outline.

The outline of Banks Peninsula, N.Z., has been considerably simplified by cliff-cutting on the ends of the spurs separating the drowned valleys on the seaward parts of its periphery (figs. 351, 401).

Further simplification of the outline results from deposition in the re-entrants of waste resulting from erosion of the headlands or

brought down by neighbouring rivers, which build deltas of the coarser portion of their load at the heads of the drowned valleys or estuaries (figs. 165, 208, 402).

Open bays have curving beaches (*pocket beaches*) around their heads, built of sand or gravel carried in from the cliffed headlands at either side. The material on a pocket beach is subject to constant grinding, and the resulting fine waste is drawn away seaward; but where the rate of supply is greater than that of loss due to grinding successive strips of beach are added, and the bay-head

C. A. Cotton, photo.

FIG. 400.—Sea-cliffs developed in the process of cutting back a headland projecting from a young coast of submergence, Bream Head, Whangarei, N.Z.

is thus prograded. As a result the beach may extend laterally so as to protect cliffs formerly subject to wave-attack (fig. 403).

Frequently bays are also bridged across near their mouths by ridges, termed *bay-bars*, or simply *bars*,* of sand or gravel stretching from headland to headland (figs. 388, 404, 405). These also protect the sides of the bays from the further attacks of ocean-waves.

* The physiographic use of the term "bar" differs from the nautical, which applies it only to a shoal across the mouth of a river. Bars of the latter kind originate in the same way as bay-bars, but the formation of a permanent and continuous exposed ridge is prevented by the outflowing current. Exposed bars are formed temporarily, however, across the mouths of some rivers.

C. A. Cotton, photo.

Fig. 401.—The southern side of Banks Peninsula, N.Z., showing cliffed headlands resulting from retrogradation of spurs separating small drowned valleys at the mouths of radial consequent streams on a dissected volcano. The coast is still young, for these bays still remain open. In the foreground is the north-eastern end of the Ninety-mile Beach.

C. A. Cotton, photo.

Fig. 402.—A bay-head delta built by the Hutt River into Port Nicholson, N.Z. The projecting miniature delta in the foreground is that of the Korokoro Stream.

Spits and Bars.—Bay-bars are formed by the growth of spits across bays. A *spit* grows outward from the lee side of a projecting headland if there is a sufficiently plentiful supply of coarse waste either broken from the headland itself by marine erosion or carried along-shore past it from some more distant source. Gravel

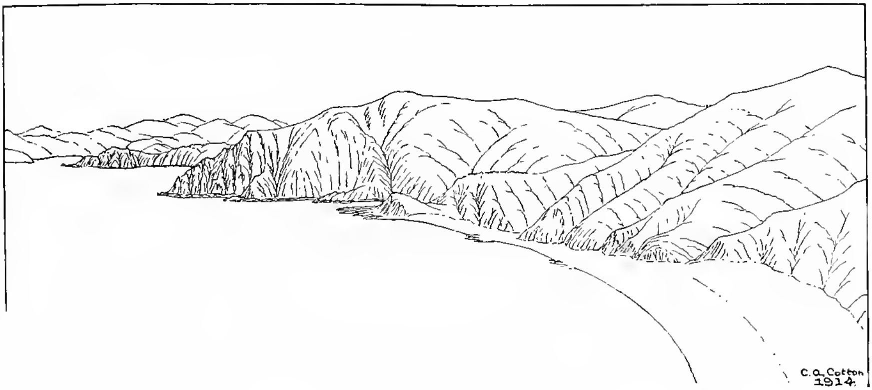


FIG. 403.—Slightly cliffed headlands and curving sandy pocket beach across the head of a shallow bay, Bay of Islands, N.Z.

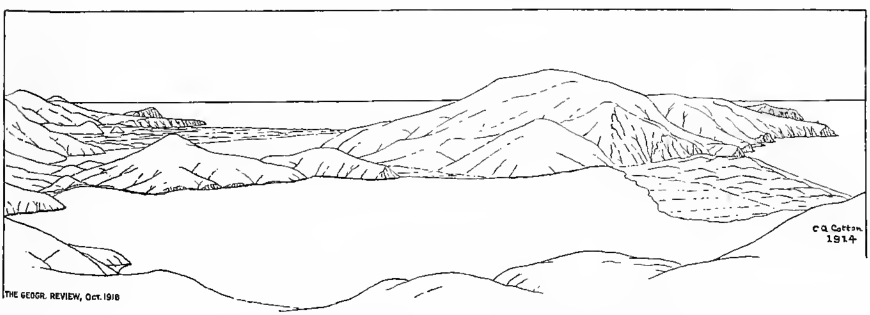


FIG. 404.—Dune-covered bars enclosing large bays (drowned valley-systems), Hooper's Inlet and Papanui Inlet, Otago Peninsula, N.Z. (see fig. 388).

or sand travelling along under the influence of the littoral current and at the beach-line within the zone of breakers comes to rest when it passes the headland, because there it is carried into the deeper water of the bay beyond, and sinks to a depth at which there is insufficient motion to stir such coarse material. The accumulation

of this waste builds at first a small salient to leeward of the projecting point. More waste travels along in the shallow water bordering the seaward margin of this salient, reaches the end of it,

C. A. Cotton, photo.

FIG. 405. — A drowned valley recently converted from a bay into a lake by the growth of a bar of gravel across the mouth, Lake Forsyth, south side of Banks Peninsula, N.Z.

C. A. Cotton, photo.

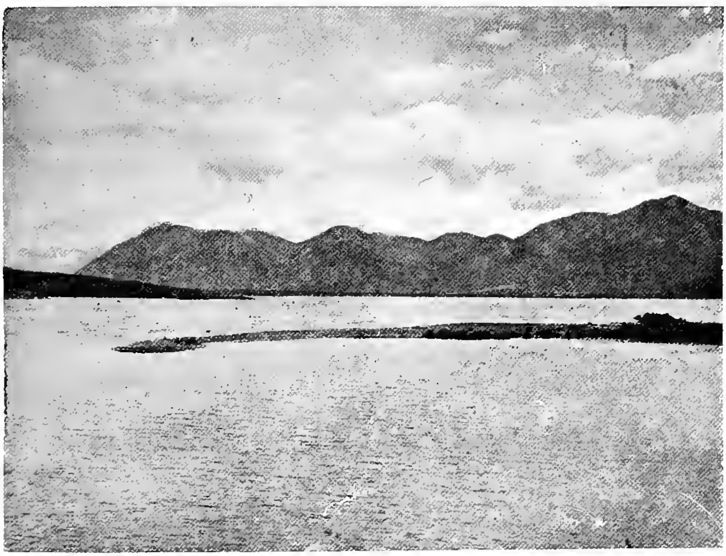
FIG. 406.—Spit (really a bar breached by a tidal channel) across the mouth of a bay, Sandy Bay, Nelson, N.Z.

and there sinks and comes to rest. The addition of this waste causes the salient to grow in length and to become a spit. Material

carried over a spit by breaking waves comes to rest in the still water on the landward side, causing the spit to increase in width somewhat, and on the shoal so formed a beach-ridge may be piled above high-water level. Most spits have thus an exposed portion (fig. 406).

Where the direction of along-shore drift changes with the winds the cliffed ends of drowned ridges are sometimes flanked by spits on both sides (*winged headlands*).

A spit that grows out far enough to encounter a transverse current or system of waves may have the material travelling along



R. Speight, photo.

FIG. 407.—Hooked spit in Lake Heron, Canterbury, N.Z.

its beach carried around the end — generally landward — so that growth continues in a direction at right angles to the proximal portion of the spit, forming a *hook*, or *hooked spit* (fig. 407).

After a hook is formed growth sometimes continues in the original line, and a long spit may have a number of landward-projecting branches.

There are numerous examples of spits around the coast of New Zealand. The largest is Farewell Spit, which stretches eastward

twenty miles from Cape Farewell. It has a slightly hooked form, convex to the north, and is built of sand derived from the west coast of the South Island. The portion above high-water level is covered with dunes. The Boulder-bank at Nelson, which encloses a system of bays (drowned valleys) known as Nelson Haven, is a long spit of gravel and boulders extending south-westward from Mackay's Bluff.

Growth of a spit across a bay converts the spit into a bay-bar, which encloses the waters of the bay (fig. 408), though when the bar is built of sand a channel is generally kept open through it by the

C. A. Cotton, photo.

FIG. 408.—Bar of gravel closing the mouth of a small drowned valley, and thus converting it into a fresh-water lake, Koangapiripiri, Pencarrow Head, N.Z.

tide. Such an opening is so shallow that it presents no permanent obstacle to the transportation of sand along-shore. The bar is, therefore, really continuous, though the exposed part of it is not.

The drift along-shore—strictly the line separating the littoral drift from the still water in the bay—guides the growing spit towards the next headland, and smooths its outline, when it becomes a bar, into a concave curve. The spit or bar "not only follows the line between the current and still water, but aids in giving definition to that line, and eventually walls in the current by contours adjusted to its natural flow" (Gilbert, 9). The concavity in the line bounding the littoral drift where it crosses the mouth of an open bay may be

so great that the bar which is eventually built across the bay is some distance from the mouth. Thus some bay-bars are built near the heads of the initial bays instead of bridging the bay-mouths.

As the headlands at each end of it are cut back, the seaward margin of the bar is cut away to a corresponding extent. Where the exposed ridge on a bar is cut through by the sea during this process the breach is soon mended with material thrown over the bar by breaking waves and coming to rest on the landward side. The bar is thus a relatively permanent feature, though the material composing it is subject to continual rearrangement.

The bridging of bay-mouths by bars (together with the cutting-back of headlands) shortens the shore-line very considerably, and simplifies it by substituting for the earlier intricate embayed outline one consisting of a few simple sweeping curves, such as may be closely followed by the along-shore currents that transport the beach-making waste. At this stage the coastal outline may be described as *graded* (Davis). The coast has passed through the stage of youth and has become *sub-mature*.

In the still waters of bays enclosed by bars the fine waste brought down by streams and carried beyond the limits of the deltas at the bay-heads sinks to the bottom and accumulates. The small waves that arise in the enclosed bay and the scour of the tides (where a channel is maintained through the bar) prevent filling up to high-water level; and under their influence the superficial layer of the bay-filling is moulded into shoals, or "banks," of sandy mud or sand with convex surfaces, lying between high-water and low-water level, separated by channels the beds of which are slightly submerged at low water (figs. 406, right, and 440).

Within the extensive drowned valley-systems of North Auckland spits and bars built of molluscan shells are of common occurrence, these being sorted by wave-action from the sandy silt and piled up to high-water level.

The higher parts of the mud-banks may be converted gradually into dry land by the growth of salt-marsh vegetation or of mangroves, which prevent erosion and favour accumulation of silt. A very small movement of uplift is sufficient to place such flats beyond the reach of the highest tides. The low-lying parts of the Taieri Plain (Otago, N.Z.), which are dead level, have originated in this way by the filling-in of a drowned valley (p. 245).

An example of a shore-line that has become practically straight at the sub-mature stage is found in that of the coast at the head of Palliser Bay, N.Z. (fig. 409). Retrogradation in weak rock has cut the coast back to an even line of cliffs, broken only by a bay with a straight gravel-bar across its mouth from headland to headland, which converts it into a lake. This bay is formed by drowning of the valleys of the Ruamahanga and Tauherenikau Rivers, and a delta built by the former river divides it in two, thus separating Wairarapa Lake from Onoke Lake, and also increasing the size of the former by raising its level (p. 198).

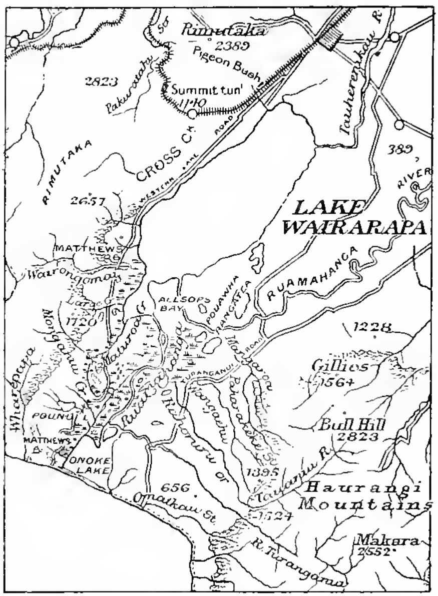


Fig. 409.—Map of the sub-mature coast at the head of Palliser Bay, N.Z., showing also Wairarapa and Onoke Lakes. Scale, 1 in. = 8 miles.

Maturity.—Retrogradation of the coast does not generally cease when the shore-line has been simplified as above described, but may continue, rapidly where the coast is formed of weak rocks, though more slowly elsewhere, until the shore-line has retreated beyond the heads of the initial bays, so that it has become a line of eroded cliffs throughout. It is then said to be *mature*.

A fully mature coast is not necessarily straight: its outline consists rather of simple sweeping curves*; for it is cut back more rapidly on areas of weak than on areas of resistant rocks, both because of the smaller resistance offered to marine erosion by the weaker rocks, and also because the weaker areas have been reduced to lower relief by subaerial erosion, so that a smaller bulk of rock has to be removed from them by the sea.

---

* See fig. 425, *DEF*, which might represent a mature coast developed by retrogradation from any type of initial coast.

This selective erosion of the weaker areas goes on throughout the course of the shore-line cycle. By the time maturity is reached the curvature due to this cause will probably have reached its maximum. Differential erosion of the weaker rocks will not take place to such an extent as to produce a deeply indented coast; for, when bays are thus formed, the land at the head of each bay is protected from erosion both by the headlands affording shelter from waves reaching the coast obliquely and also by the focussing of wave-energy on the headlands and bay-sides, rather than the bay-heads, as a result of the refraction of waves, previously described (p. 374). Thus only broad "bights" on the larger areas of weak rocks and broadly open bays on the smaller can result from marine erosion.

By the time a coast is mature many of the small irregularities of steep, young cliffs disappear, for with continued retrogradation the width of the continental shelf increases, waves running in over the shelving bottom lose energy, and the rate of cliff-retreat becomes slow. Subaerial erosion is then not outstripped by marine erosion, but is capable of reducing the steepness of the cliffs and smoothing their outline by grading the slopes.

The shore-line cycle need not be followed beyond maturity, for "old age" is not reached until the land is cut entirely away.

Barrier (Coral) Reefs and Atolls associated with Coasts of Submergence.—Coral reefs superficially similar to fringing reefs (p. 387), but separated from the land by strips of water (*lagoons*), which may be of any depth up to 20 fathoms and more, and of any width from a fraction of a mile to many miles, are termed *barrier reefs* (fig. 410). They are of frequent occurrence surrounding volcanic islands in the tropical part of the Pacific Ocean (Tahiti, for example, has, at Papeete, an excellent harbour formed by a barrier reef), and an exceptionally large one, the Great Barrier Reef, extends for about a thousand miles along the coast of Queensland.

The observed fact that reef-building corals cannot live at depths much greater than 20 fathoms raises a difficulty as to the nature of the foundation on which the growth of barrier reefs began; for it is evident in most cases that the reefs must be a great deal more than 20 fathoms thick, and that but for the presence of the reef

the depth of water on its site would be very much greater than the depth at which the growth of a reef can begin.

There is the same difficulty as to the nature of the foundation on which the growth of coral began in the building of *atolls*—coral reefs of another type, also common in the Pacific, which form more or less regular rings, and occur isolated and surrounded by water of greath depth, though the water in the lagoon within the encircling reef is relatively shallow. The only "land" associated with atolls is built of coral sand and fragments broken and piled upon parts of the reef-ring by wave-action. The "low" islands of the tropical

J. A. Thomson, photo.

FIG. 410.—A barrier reef enclosing a small and shallow lagoon, Upolu Island, Western Samoa. The reef is defined by the line of surf, and the lagoon is on the left. The small outlying island is Fanuatapu.

Pacific, as distinguished from the "high," volcanic islands, are the exposed parts of atolls.

Theories postulating the existence of numerous steep-sided and flat-topped submerged mountains, with their tops at a depth of 20 fathoms, seem scarcely worthy of consideration,* and it is generally considered that atolls and barrier reefs must have originated in the same way.

* The existence of such a slightly submerged mountain beneath the atoll of Funafuti has been disproved by boring.

Among the theories put forward in explanation of atolls and barrier reefs that of Darwin accounts most satisfactorily for the features of the majority of Pacific reefs, though it cannot be asserted that no barrier reefs or atolls were formed otherwise. According to Darwin's theory, continued upgrowth of coral takes place during slow subsidence on the site of what was originally a fringing reef, so that it becomes a barrier reef, or, in the case of a reef surrounding an island, becomes eventually an atoll when the island is completely submerged (fig. 411). The ring-like form of the reef, enclosing a lagoon, is accounted for by the more vigorous growth

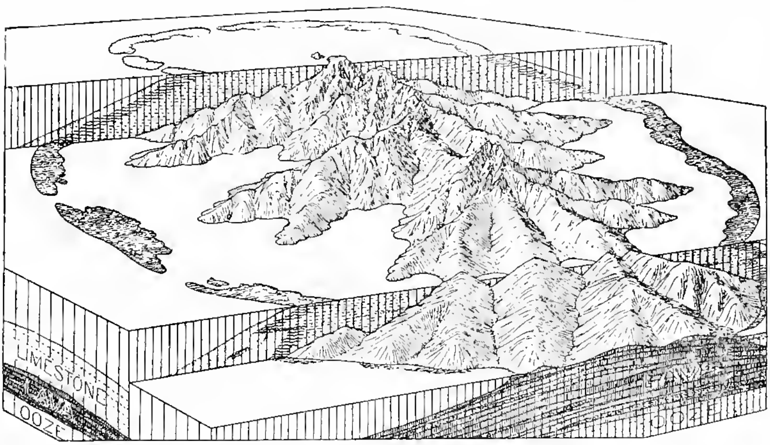


FIG. 411.—Evolution of a barrier reef, and eventually an atoll, from a fringing reef during slow subsidence of a dissected volcanic island (the subsidence being shown as a rise of sea-level relative to the land). Front block, fringing reef; middle block, barrier reef; rear block, last stage of submergence of the island—the almost-atoll stage. (After Davis.)

of the corals around the periphery, where there is a continual and abundant supply of pure sea-water and food. Inside this ring of growing coral the bottom is built up only by the growth of slower-growing organisms and the accumulation of waste, which is wholly derived from the reef in the case of an atoll, but from both reef and land in the case of a barrier reef.

Recently an extensive study of the coral reefs of the Pacific has been carried out by Davis (39), who has come to the conclusion that the theory of subsidence with little or no modification explains

satisfactorily all the barrier reefs examined by him. Strong evidence in its favour is found in the fact that the coasts bordered by barrier reefs are always coasts of submergence—a confirmation of Darwin's theory that was first pointed out by Dana. When, also, uplifted barrier reefs (numerous examples of which are known) are examined, the basement on which they rest—*i.e.*, the bottom on which coral-growth began—is always found to have been a submerged erosion-surface, which must have sunk progressively as the reef was built up above it.

There is much evidence of diverse movement in the Pacific region, some parts having sunk as others rose or remained stationary, while in other cases tilting occurred. Acceptance of a theory of subsidence in explanation of barrier reefs and atolls does not, therefore, necessitate belief in universal subsidence of the bottom or general rise of sea-level in the vast Pacific area.

The coasts of submergence bordered by barrier reefs are protected from attack by ocean-waves. The headlands (partly submerged ridges and spurs) which project into the lagoon are, therefore, but little cliffed. When subsidence ceases, or there is a pause, deltas grow at the bay-heads and smooth the outline of the coast. If renewed subsidence takes place it will, however, submerge these and restore the embayed outline. Practically all the waste of the land is entrapped in the lagoon, and in a long period of still-stand it will be quite filled by the outgrowing, confluent deltas.

Outside the reef there is generally a very steep slope down into deep water. This is a talus slope of fragments broken by wave-action from the reef. In periods of still-stand this waste is built out to form a narrow "continental" shelf.

Darwin's theory of subsidence is not accepted by all modern investigators as a satisfactory general explanation of the formation of coral reefs and atolls; but limitation of space precludes a statement or discussion of the rival theories here.

CHAPTER XXIX.

COASTAL OUTLINES (*continued*), AND THE SHORE-LINES OF LAKES.

Uplifted coasts, or coasts of emergence. Coasts of emergence in New Zealand. Contraposed shore-lines and multi-cycle coasts. Dissection of sea-cliffs. Ancient sea-cliffs. Fault coasts. Juxtaposition of diverse coastal types at Port Nicholson. Multi-cycle fault coasts in New Zealand. Volcanic coasts. Fiord coasts. Prograded coasts. Alluvial prograded coasts. Progradation following grading of the outline. Artificial progradation. Cuspate forelands. Island-tying. Compound coasts. Lake-shores.

Uplifted Coasts, or Coasts of Emergence.—The initial shore-line of a coast of emergence is the simple line traced by the sea-margin along an exposed sea-floor, which is the former continental shelf unless the amount of emergence is unusually great (fig. 382, *C*).

The succession of sequential forms developed from a shore-line so initiated is not the same in all cases, but varies with the steepness of the profile of the sea-bottom seaward from the new sea-margin. If the seaward slope of the initial sea-floor is very gentle an off-shore bar is thrown up in the process of grading the profile (p. 389), and lagoons are thus enclosed, which may form serviceable harbours in the vicinity of river-mouths, where channels of sufficient depth are scoured out and kept open by currents. Later a deficiency in the supply of waste may cause the waves breaking on the off-shore bar to erode it, cutting away both it and the low or dune-covered land of the partially filled lagoon and coastal plain behind. In that case a line of low cliffs is developed. The shore-line remains simple; no conspicuous irregularities will be developed by erosion on the soft material forming the shore. If the seaward slope of the initial sea-floor in front of the uplifted coast is somewhat steeper, the development of the graded profile in the early stage of coastal evolution will demand erosion at the shore-line instead of off-shore. Retreat

C. A. Cotton, photo

Fig. 412.—General view of "raised beach" and rock platform uplifted in 1855, southward from Breaker Bay, Miramar Peninsula, Wellington, N.Z.

C. A. Cotton, photo.

Fig. 413.—Raised storm-beach of gravel partly covered by vegetation since uplifted in 1855, near Breaker Bay, Wellington, N.Z.

(retrogradation) of the shore-line begins at once and cliffs are formed, low at first, but increasing in height as the sloping coastal plain is cut back (fig. 382, *E*). As long as the soft material of the coastal plain is being eroded the shore-line remains simple.

While rapid cliff-retreat is in progress the courses of streams entering the sea are constantly being shortened, and the streams rejuvenated. The larger rivers succeed in degrading so as to enter the sea at grade, and may even keep their valley-mouths

C. A. Cotton, photo.

FIG. 414.—Sea-cliff and caves cut prior to the uplift of 1855, western side of Palliser Bay, N.Z.

opened out to a mature cross-profile. Smaller, steep-grade streams on the other hand, are often betrunked by cliff-recession, and either descend the sea-cliffs as cascades falling from the mouths of sharply cut-off hanging valleys of varying height (according to the stream-gradients), or perhaps have succeeded in cutting notches in the lips of their hanging valleys (fig. 382, *E*).

Coasts of Emergence in New Zealand.—In New Zealand a cliffed coast of emergence bordering a typical coastal plain of simple structure occurs in western Wellington and Taranaki, but

the coastal-plain deposits are thin, and the cliffs have retreated so far that the underlying rocks are exposed in them.* These underlying rocks are as weak as the coastal-plain deposits, and so the coastal features closely resemble those of a cliffed coast of emergence of the simplest type, though strictly the coast belongs to the class described below as contraposed.

A short strip of coast at Cape Turakirae (p. 384) is a coast of emergence of such recent origin that it retains its initial form. As noted previously, it is formed by the uplift of an exceedingly steep sea-bottom (figs. 375, 376).

Around the shores of Port Nicholson and neighbouring parts of the outer coast near Wellington a new strand-line resulted from

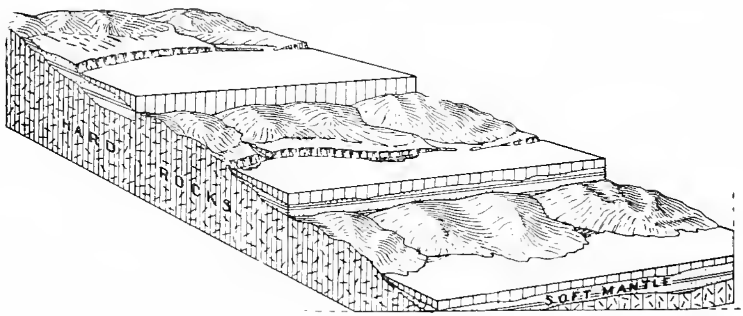


FIG. 415.—Diagram of a contraposed shore-line developed from a coastal plain of sediments overlying a former land-surface of considerable relief. Earliest stage (upper part of diagram), cliffed coastal plain; second stage (middle part of diagram), contraposed shore-line developed; third stage (lower part of diagram), the sea beats against the irregular surface of the undermass after complete removal of the coastal-plain sediments by erosion. (After Clapp.)

a movement of uplift of 5 ft. which took place suddenly in 1855 (Lyell, 56), causing a severe earthquake at Wellington. Owing to the small measure of this uplift the coast of emergence formed by it does not have the typical simple outline, but still follows that of the former shore-line, which in and about the entrance to Port Nicholson was that of a young depressed coast (fig. 412). It is very interesting, however, because the inner margin of the wave-

* The coastal-plain deposits are the Hawera series and the underlying rocks the Wanganuian of geologists. The latter consist chiefly of a bluish clay known locally as "papa."

cut rock platform (above which rise in some parts numerous stacks), the sea-cliffs with rock-arches and sea-caves, and the convex storm-beaches of gravel piled by breaking waves high above former high-water level (fig. 413) are now beyond the reach of waves and are partly covered by vegetation.

The uplift of 1855 affected the shore-line as far as the head of Palliser Bay, on the western side of which the uplifted shore-line may still be traced (fig. 414).

Contraposed Shore-lines and Multi-cycle Coasts.—Retrogradation of a coast of emergence may continue until the "undermass" of

C. A. Cotton, photo.

Fig. 416.—A multi-cycle coast of emergence, between Baring Head and Cape Turakirae, Wellington, N.Z.

older rocks beneath the coastal-plain sediments is exposed at the base of the sea-cliffs. A *contraposed shore-line* (Clapp, 27) is thus developed (fig. 415).

In fig. 415 the results of a continuation of retrogradation after the rocks of the undermass are exposed are not shown. Retrogradation may now, however, be expected to continue vigorously (though probably more slowly), for the supply of waste will diminish when the sea is no longer attacking the easily eroded covering beds

directly. As a result the rock of the undermass will be exposed in the cliffs to an increasing height.

If the coastal plain thus in course of destruction by marine erosion be an uplifted continental shelf the landward margin of which is a cut platform with only a thin veneer of waste (such as is shown in fig. 374) it will be eventually reduced to a bench which is a remnant of the cut platform (figs. 372, 373). This will generally be covered with a veneer of waste; but this waste is not

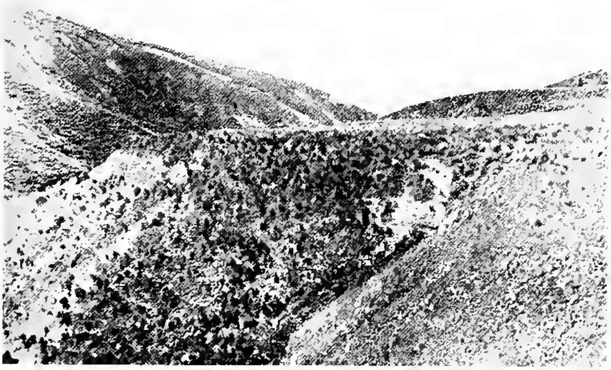
C. A. Cotton, photo.

FIG. 417.—Sea-cliffs of a contraposed shore-line, Tongue Point, Wellington, N.Z. There is a thin layer of marine gravel on the uplifted rock bench, overlying the old rocks forming the cliffs.

necessarily that which was there before emergence began, for the waste has generally been reworked during emergence into beach or littoral deposits (fig. 417).

When the newly-cut cliffs are separated only by such a narrow bench from ancient cliffs of the former shore-line cycle the coast may be aptly described as a *two-cycle* coast. It has *two-storied* cliffs. *Multi-cycle* coasts, with cliffs of three or more stories, may also occur (fig. 416).

Contraposed shore-lines in the early stage of development at which the rocks of the undermass are exposed at the base of cliffs of coastal-plain sediment occur in New Zealand along the coast of western Wellington and Taranaki (*e.g.*, at Patea and Hawera), and at places on the east coast of Otago. At Oamaru, for example, the so-called "12 ft. raised beach" is a gravel-bed resting on the rock floor at the base of thin coastal-plain sediments. It is thus a "fossil" beach, and is more ancient than the surface of the coastal-plain remnant the landward margin of which forms the "42 ft. raised beach."



C. A. Cotton, photo.

Fig 418.—A small valley rejuvenated by cliff-recession, near Cape Campbell, N.Z. View looking down-valley to the sea. The bench in the centre is a remnant of the former valley-floor.

Remnants of cut platforms with contraposed shore-lines in a later stage of their development are found at many places around the coasts of New Zealand. They are common near Wellington (figs. 372, 373, 416, 417). They are not continuous, but in places have been cut away entirely, so that the sea beats again at the base of cliffs of a former shore-line cycle.

Considerable irregularity of outline may be developed after a shore-line becomes contraposed. As shown in fig. 415, removal of the cover from an uneven floor may produce this result. As

retrogradation proceeds farther, if rocks of varying resistance, or occasional weak structures, are present in the undermass (or rocks of the old land), and these are etched out by differential erosion, small bays, caves, and outrunning points and reefs will diversify the shore-line, and broad re-entrants and salients may also come into existence, marking the positions of areas of weak and resistant rocks (p. 416); but, as previously explained, marine erosion cannot develop bays that are landlocked or extend inland to any great depth as compared with their width.

C. A. Cotton, photo.

FIG. 419.—Another view of the rock bench of the multi-cycle coast at Tongue Point, Wellington, N.Z., seen in fig. 417, showing its immature dissection and the ancient sea-cliff behind it. The ancient cliffs are here "two-storied," for there is a higher uplifted rock bench, similar to that in the foreground, but more maturely dissected, separating the most ancient cliff at its rear from the newer but maturely dissected cliff, fringed by fans, at its front.

Dissection of Sea-cliffs.—Normal erosion operates while cliff-recession is still in progress, and young ravines cut even the cliffs of a mature shore-line into facets (fig. 417). During retrogradation the dissecting valleys are constantly rejuvenated by cliff-recession (fig. 418), though the smaller streams frequently cascade from the mouths of hanging ravines (p. 423).

Ancient Sea-cliffs.—Where emergence takes place and the sea retreats from the base of cliffs previously receding, and, therefore, freshly cut, the cliffs are subject henceforth to subaerial erosion only.

After withdrawal of the sea has brought retrogradation to an end, rejuvenation due to cliff-recession ceases; and lowering of the local base-levels due to entrenchment of the extended streams across the emergent shelf, though it quickly affects the larger rivers of the old land (p. 220), is not much felt by the smaller streams arising on and dissecting the sea-cliffs until the newly formed coastal plain has been narrowed considerably by recession of cliffs in the new shore-line cycle. Meanwhile dissection of the ancient sea-cliff goes on on similar lines to the dissection of a fault-scarp (p. 157). The

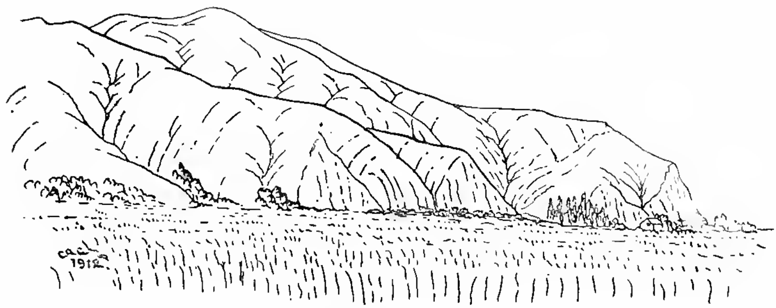


FIG. 420.—Ancient sea-cliffs bordering the former extension of Cloudy Bay, N.Z., now occupied by the delta of the Wairau.

slope is reduced at first by crumbling of the cliff and accumulation of talus along the base (fig. 195). The minor irregularities, caves, &c., of a rocky shore are thus soon obliterated. The cliff is then dissected into a succession of steep, blunt spurs separating steep-graded ravines, at the mouths of which fans are spread on the uplifted rock bench or coastal plain (fig. 419.)

At the same time weathering crumbles away projecting stacks on such portions of the rock bench as are not buried by the talus and fans, making the undissected parts of it flat.

Cliffs from which the sea has been forced to withdraw owing to the building of deltas or the occurrence of marine progradation fade away in a similar manner (fig. 420), except that their ravines are not liable to be deepened by the headward erosion of streams

while, on the other hand, accumulation of blown sand or of delta deposits may bury the cliff-base and cause some aggradation of the dissecting streams.

Fault Coasts. -- The initial form of a fault coast is a fault-scarp facing the sea (fig. 421). As it is easy to imagine cases in which the earth-block to seaward of the scarp is incompletely submerged (fig. 422), and in which that to landward is partly submerged (figs. 421, *B*, and 423), and others in which the fault dies

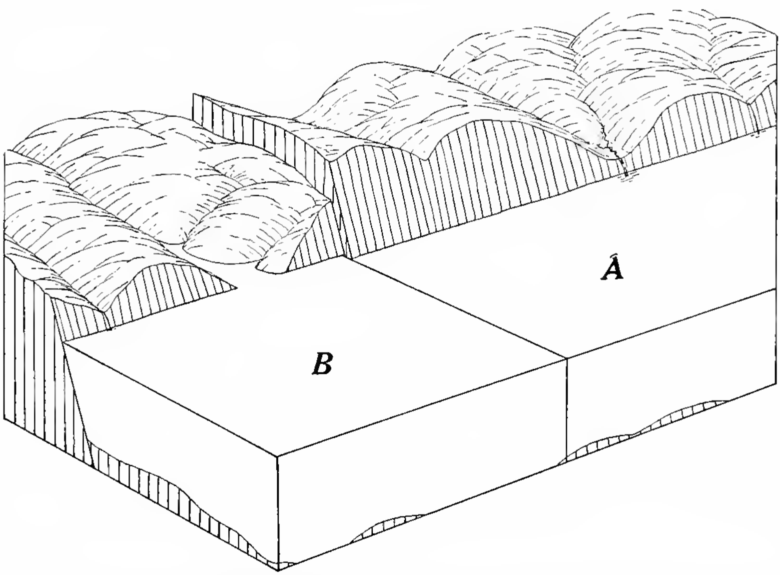


FIG. 421.—Two initial fault coasts. In block *A* the landward area has risen or has remained stationary, while in block *B* it is slightly depressed. The seaward area is depressed to the same extent in *A* and *B*.

out when followed lengthwise (figs. 422, 424), or passes inland, it is obvious that there must be transition forms between clear-cut fault coasts and coasts of submergence and emergence.

At first a fault coast must trace a very simple if not quite a straight line—simpler than the line of a maturely retrograded coast, for it will pass indifferently across areas of weak and resistant rocks; but, as the coast will be subject to energetic wave-action and will be rapidly eroded during the process of grading the off-shore profile, it will quickly lose some of its points of resemblance to a

fault-scarp on the land-surface, and will resemble other retrograded coasts more and more closely. A fault coast quickly passes through its stages of youth and becomes mature (figs. 425, 426). Fault

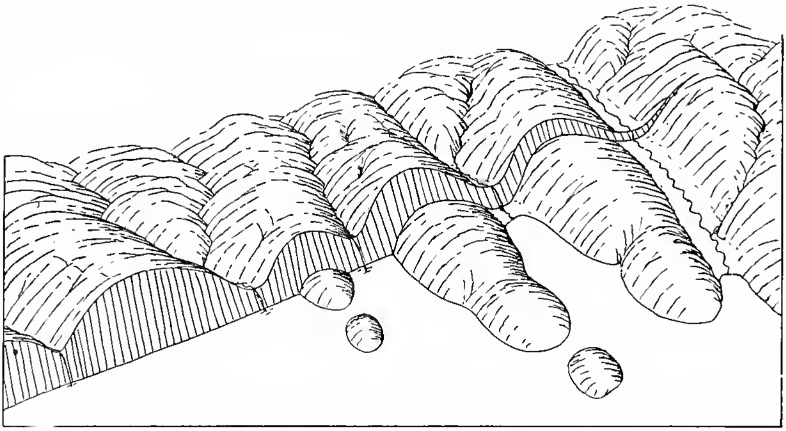


FIG. 422.—A fault coast (on the left) formed by a fault diminishing in displacement towards the right, where drowned topography appears seaward of the scarp, and the fault dies out inland.

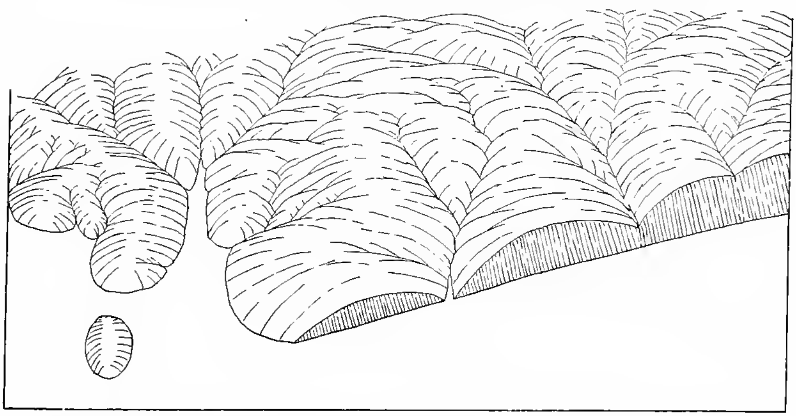


FIG. 423.—On the right a fault coast, which, owing to downward tilting of the landward area towards the left, passes in that direction into a coast of submergence.

coasts are sometimes recognizable owing to their cutting obliquely across the strike of the rocks (though all fault coasts do not necessarily do so), and also owing to captures and other disturbances

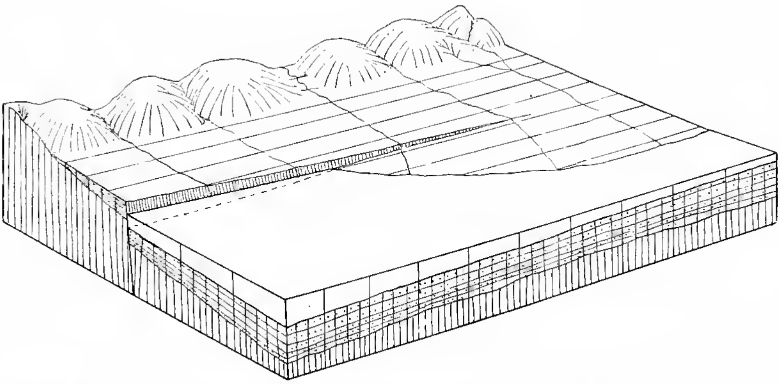


FIG. 424.—A fault coast (on the left) formed by a fault-scarp diminishing in height and dying out towards the right, where the coast passes into a coast of emergence.

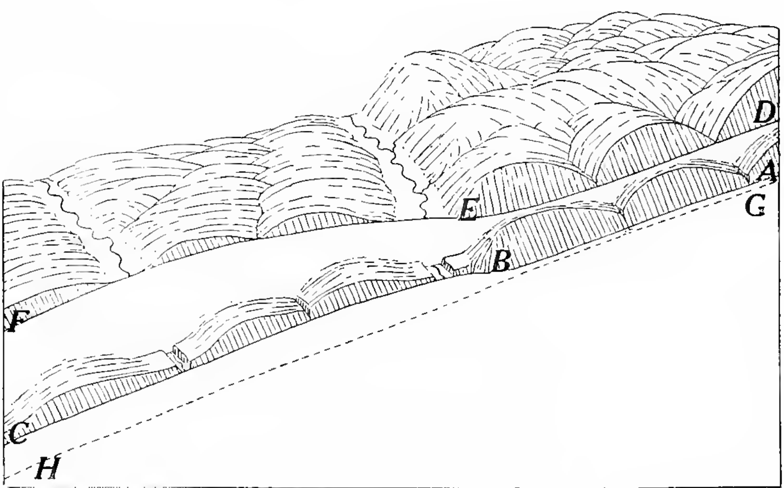


FIG. 425.—Development of an embayment of the shore-line of a mature fault coast in an area of weak rocks. *AB*, resistant rocks; *BC*, weak rocks; *DEF*, form of shore-line at a later stage; *GH*, line of initial shore, determined by a fault. In the pre-faulting cycle of normal subaerial erosion the area of weak rocks had been reduced to much lower relief than the area of resistant rocks.

in the drainage-systems in the coastal districts due to subsidence of the former continuation of the land to seaward (fig. 427).*

In New Zealand the coasts bounding the Wellington district, eastern Marlborough, and the west coast of the South Island, together with the eastern shore of the Firth of Thames, appear to be derived from fault coasts, though some parts are now prograded and some parts have been affected by later uplifts—as is shown by the presence of contraposed shore-lines with uplifted cut platforms (p. 427), so that they may be described as fault coasts in a second (or later) cycle of marine erosion introduced by simple uplift (fig. 428). The western coast of southern Wellington (fig. 381) cuts obliquely in a north-easterly direction across the more northerly

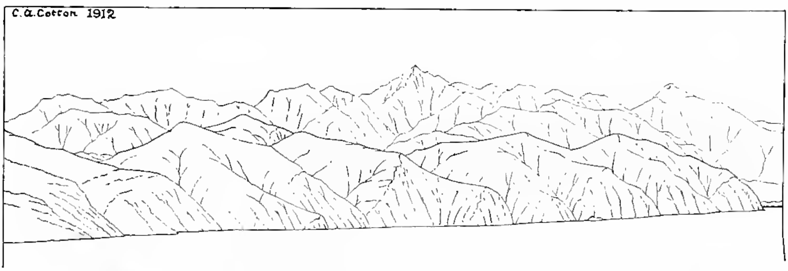


FIG. 426.—Mature coast northward of Amuri Bluff, apparently developed from a fault coast.

trend of the larger, longitudinal topographic features of the land-surface (fig. 170), as a fault coast may be expected to do, and several streams of both the western and southern coasts in the vicinity of Wellington reach the sea by very roundabout courses (fig. 170; compare with fig. 427).

Juxtaposition of Diverse Coastal Types at Port Nicholson.—Port Nicholson, the harbour of Wellington, N.Z., has been formed by a deep local subsidence bounded along the north-west side by a strip of fault coast (figs. 170, 171, 429), and elsewhere by warped surfaces resulting in coasts of submergence (figs. 436–438). The outer coast flanking the Port Nicholson depression on either side is, however, a coast of emergence at the "contraposed" stage.

* The expectable features of fault coasts are more fully set out in an article by the author, "Fault Coasts in New Zealand," 88.

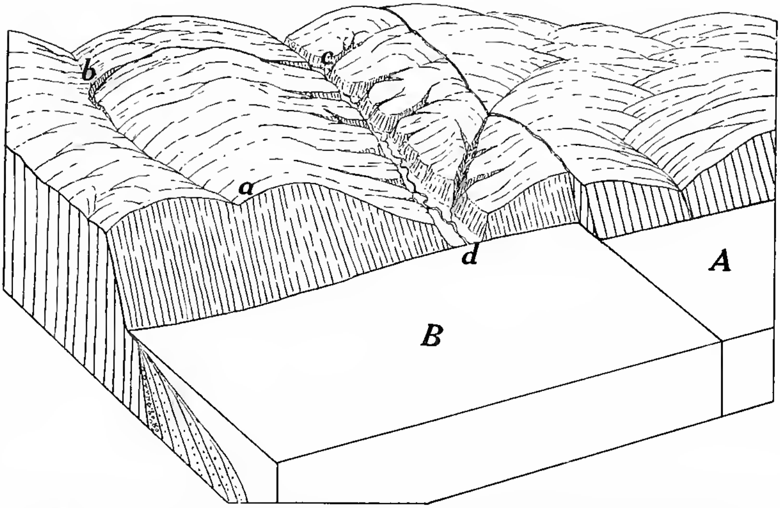


Fig. 427.—An early sequential form, block *B*, developed from an initial fault coast, block *A*. In block *B* the inland-flowing stream *ab*, already beheaded by faulting, has been captured by a tributary *bc* of the revived seaward-flowing stream *cd*.

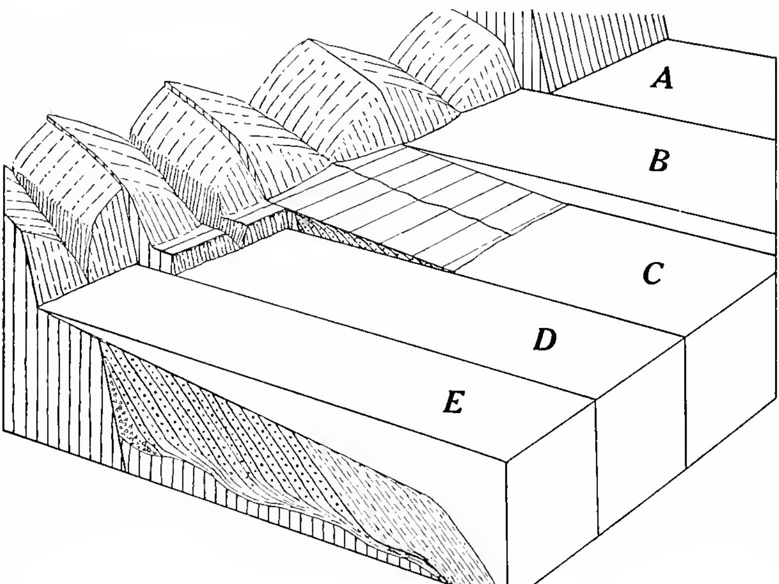


Fig. 428.—A two-cycle fault coast. *A*, initial form of first cycle; *B*, early maturity; *C*, the same after emergence; *D* and *E*, sequential forms in the second cycle.

Figs. 430 and 431 show tilting of the uplifted cut platforms in the neighbourhood of Baring Head towards the down-warped area.

Multi-cycle Fault Coasts in New Zealand.—As mentioned above, many parts of the New Zealand coast-line, of which the general outlines were determined most probably by faulting, are in the current cycle coasts of emergence showing multi-cycle forms. Of this kind are the coasts of eastern Marlborough, the Wellington Peninsula, and parts of the west coast of the South Island.

Volcanic Coasts.—Volcanic coasts, initiated by either accumulation of fragmental volcanic material or flows of lava with slopes descending into the sea, need not be discussed at length, for the general principles of shore-line development already outlined

C. A. Cotton, photo.

Fig. 429.—Fault coast forming the north-western boundary of the Port Nicholson depression, Wellington, N.Z.

apply to them. The initial profile will be somewhat steep, and so cliff-cutting will begin at once. Islands of scoria, the summits of submarine cones, which occasionally rise above the surface, yield so readily to erosion that, when accumulation ceases for a time, they are quickly reduced to shoals—the old-age stage of coastal development. Lava rocks are much more resistant to wave-action. Small salients of the shore-line formed by lava-flows may exist initially with bays between them, as on the southern side of Lake Roto-a-ira, N.Z., which is formed by lava-flows from Mount Tongariro; but these will soon be smoothed out as the coast is cut back; and unbroken lines of steep cliffs result, resembling those between the

drowned valleys of the partly submerged volcanic island forming Banks Peninsula (fig. 401).

Fiord Coasts.—Where the sea enters a deeply excavated glacial trough after the melting-away of the glacier a *fiord* results.*

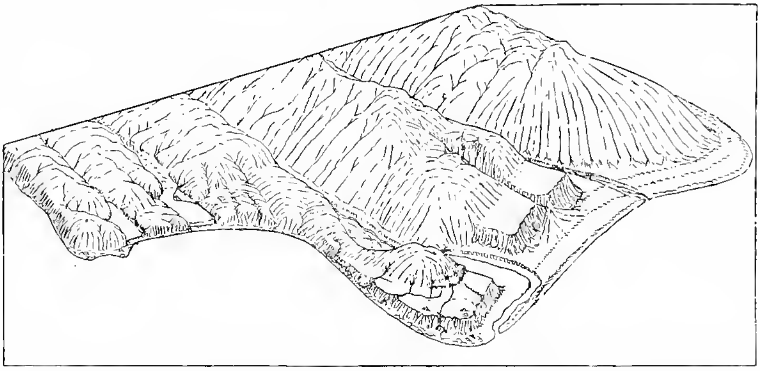


Fig. 430.—Diagrammatic sketch of the coast to the east of the down-warped Port Nicholson depression, showing tilting towards the depression (to the left). Baring Head is in the centre.

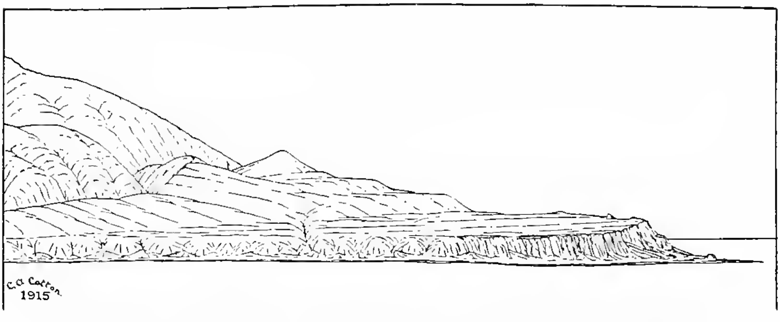


Fig. 431.—Uplifted coastal rock platforms at Baring Head, Wellington, N.Z., tilted by the warping that formed the Port Nicholson depression.

The peculiar features of a *fiord coast* are all within the embayments so formed. The outer coast may be of any of the ordinary types.

* Though subsidence of the land may accentuate the irregularity of the shore-line in a fiord district by drowning glaciated troughs, or portions of such troughs, excavated above sea-level, and has, no doubt, done so in many cases, it is not necessary to assume subsidence to account for all fiords, for it has been shown by Gilbert that glaciers may excavate troughs to a very considerable depth below sea-level (45, pp. 210, 218).

FIG. 432.—Panoramic view of Milford Sound, N.Z., showing Mitre Peak (left) and the northern side of the fiord. Angle of view, west to north.

In New Zealand the westward-facing coast of the south-western corner of the South Island is indented by fiords, one of the finest examples of which is Milford Sound (figs. 285, 432, 433).

The sides of true fiords differ in no essential respect from those of glacial troughs cut entirely above sea-level. The profiles of their floors generally confirm also their glacial origin. Most fiords, like many of the lakes now occupying glacial troughs, but unlike the majority of rias and others arms of the sea, still preserve their under-water profiles but little altered by sedimentation. This is partly because of their great initial depth and holding-capacity, and partly because of the shortness of the interval (since the melting-away of the ice) during which sediment has been accumulating in them. In the New Zealand fiords small deltas occur at the heads, but elsewhere depths of from 1,000 ft. to 2,000 ft. are commonly met with.

Towards the mouth the depth becomes less, the bed-rock floor probably rising in that direction, as it does in many of the glaciated valleys occupied by lakes (p. 325), while there is probably present also a submarine terminal moraine.

The sides of fiords which, like those of south-western New Zealand, are cut in resistant, unjointed rocks and have nearly

C. A. Cotton, photo.

FIG. 433.—View looking up Milford Sound, N.Z., a typical fiord. The Stirling Falls (500 ft.) spout from the mouth of a hanging valley on the extreme left, and the sheer precipice beside them is 3,000 ft. high.

vertical walls exhibit the initial form very little, if at all, modified by marine erosion (p. 377). Beaches are rare, and occur only where subaqueous talus slopes augmented by unusually plentiful supplies of waste brought in by streams accumulate up to sea-level. In

Milford Sound two streams of considerable size plunge as falls from the mouths of hanging valleys which open at a height of 500 ft. on the fiord-walls—Stirling Falls (fig. 432, left of centre; also fig. 433) and Bowen Falls (fig. 434). The Stirling Falls reach the sea in a single leap.

Muir and Moodie, photo.

Fig. 434.—Bowen Falls, Milford Sound, N.Z., seen across the delta at the head of the fiord.

Fiord coasts may be expected to go through a cycle of shore-line development like that of coasts of submergence, the outline becoming graded, the embayments filled, and the coast being eventually cut back, if retrogradation continues long enough, to a mature outline. As noted above, however, existing examples are in an extremely young stage of their shore-line cycle.

Prograded Coasts.—Progradation, which, as previously noted (p. 391), may occur when there is an over-abundant supply of waste and the off-shore profile is not very steep, causes considerable changes in coastal outlines. A gently sloping profile of equilibrium may have been developed under previous conditions of less abundant waste-supply, and so progradation may take place in front of the sequential forms of coasts originating in various ways (p. 392).

In some cases progradation is caused by the outgrowth of deltas, either separate or confluent, forming *alluvial prograded coasts,* while in others the material built into forelands, though in part supplied by streams, is transported and sorted by waves and currents before being thrown up on an advancing shore-line.

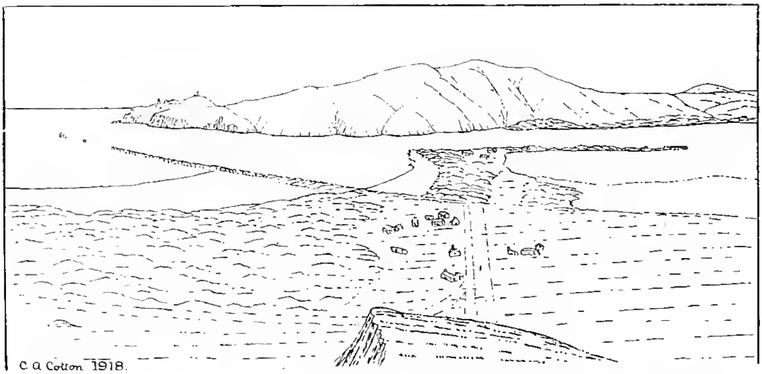


FIG. 435.—Cuspate foreland partly closing the entrance to a drowned valley (Otago Harbour, N.Z.). Note the spit projecting into the harbour from the extremity of the foreland.

Alluvial Prograded Coasts.—The shore-line of an alluvial coast built of coarse material is generally simple, the only irregularities being the salients formed by the fronts of deltas, which may be very broadly rounded off. A broad rounded salient is formed, for example, by the delta of the Waitaki River, N.Z. This delta has been modified slightly in outline, however, by retrogradation, which has cut a line of low cliffs in the alluvium. The modern delta of the Clarence River (p. 207), small though it is, forms a more pronounced salient. The outline of the margins of the confluent deltas forming the Canterbury Plain has been smoothed out by the movement of the shore drift to form the Ninety-mile Beach. In

the case of such deltas built of coarse material the off-shore profile remains sufficiently steep to allow energetic waves at the shore-line to prevent the growth of minor irregularities.

Deltas of fine material, on the other hand, may have very irregular shore-lines (the well-known digitate delta of the Mississippi, for example), where the natural levees of many distributaries grow out rapidly into the shallow water covering the broad subaqueous portions of the deltas, in crossing which waves have lost much of

C. A. Cotton, photo.

Fig. 436.—Cuspate foreland built in front of a young depressed coast, eastern shore of Port Nicholson, N.Z. The foreland stretches out towards Ward Island.

their energy, so that they are powerless to erode and smooth the outline of the shore. Deltas advancing into shallow water are generally fringed also by sand-bars enclosing lagoons (*e.g.*, the deltas at the head of Tasman Bay, N.Z.) (fig. 214).

Progradation following Grading of the Outline.—When the outline of portions of a coast becomes graded transportation along-shore is facilitated, and so great a supply of waste to some parts of the

coast may result as to cause progradation. All the material thrown up by waves and built into a prograded coast is not shore-line drift, however. Some may have been moved by off-shore currents along the continental shelf (at depths at which wave-motion appreciably stirs the water in contact with the bottom). Where a very abundant supply of such waste necessitates rapid deposition to maintain the profile of equilibrium accumulation may take place at the inner as well as the outer edge of the shelf. From the material thrown landward the finer particles are winnowed by wave-action and carried away in suspension, to be redeposited seaward, leaving the coarser sand-grains to be piled up as a beach along with the shore-drift.

The outline of a prograded coast may be a smooth curve from one projecting headland to another, or a similar curve may end

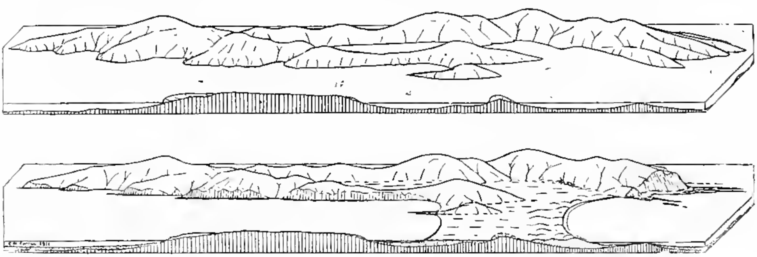


Fig. 437.—Diagram showing the conversion of Miramar "island" into Miramar Peninsula, Wellington, N.Z.

tangent to a retrograded coast, along which progradation encroaches as the foreland already existing increases in width (fig. 378). The curve of the shore-line is determined by the sweep of the littoral current, and where there are eddies or conflicting currents the outline is made up of two or more curves intersecting.

Artificial Progradation.—Walls, or groins (fig. 439), at right angles to a beach, are sometimes constructed to cause artificial progradation as a check to cliff-recession where coastal towns are in danger of being engulfed. The shore drift cannot pass the obstruction until the shore-line has been built out in a sweeping curve to the seaward end of it, and a beach formed, along which transportation can take place.

The Timaru (N.Z.) Harbour moles have acted in this way, forming a trap, southward of which an extensive strand-plain has

been built of gravel. Northward of Timaru the shore-line is now suffering retrogradation because the supply of waste formerly travelling northward along the beach has been thus cut off. The total cessation of the supply of gravel has caused the beach at Caroline Bay, immediately to leeward of the Timaru harbour-works, to be covered with sand, forming the only sandy beach for many miles.

Cuspate Forelands. — Where conflicting currents meet — eddies, generally, of ocean or tidal currents—progradation commonly takes

C. A. Cotton, photo.

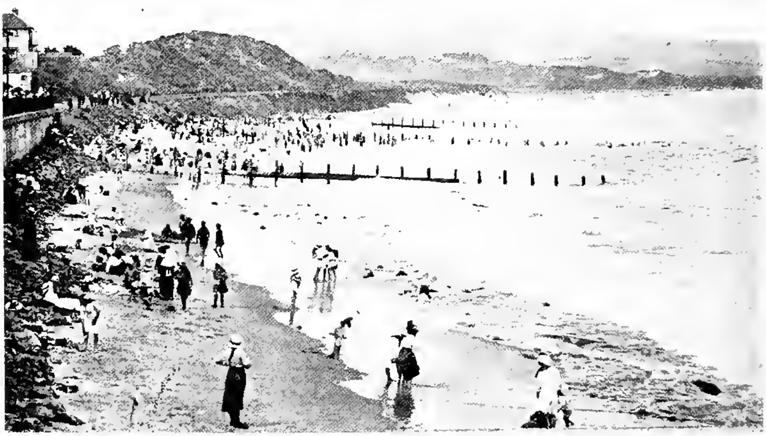
FIG. 438.—Southern end of Miramar Peninsula and the sand isthmus, or tombolo, connecting it with the mainland, Lyall Bay, Wellington, N.Z.

place, and a projecting foreland is built out, either as a local incident in an otherwise retrograded coast or as a salient of a continuous foreland. Though sometimes rounded at the end, such a salient is bounded typically by the two curves followed by the littoral currents, tangent to the general line of the coast some distance away from the projection at either side, and sweeping out to intersect each other in a sharp cusp at its extremity. Such a *cuspate foreland* may form part of a barrier or may spring from the main shore-line (figs. 435, 436). It may be formed by the

confluence of two spits, which enclose a lagoon, or may be built out solidly by the growth of successive beaches.

An outlying island seems sometimes to have caused the eddy currents which determine progradation. A large cuspate salient of the foreland forming the coastal lowland of western Wellington, N.Z., points towards Kapiti Island.

Island-tying.—Outgrowth of a spit from a headland results sometimes in the formation of a bar or isthmus connecting a former island with the mainland; while in other cases similar



F. G. Radcliffe, photo.

FIG. 439.—Dune-covered sand isthmus, or tombolo (middle distance), connecting Otago Peninsula, N.Z. (in the distance on the right) with the mainland.

island-tying takes place as a result of continued outgrowth of a cuspate foreland from the mainland; or the spit or foreland may grow from the island towards the mainland. A great many peninsulas are *land-tied islands*, each connected to the mainland by an isthmus formed thus. A sand or gravel isthmus formed by the growth of a spit has been termed a "tombolo" (Gulliver, 48).*

Miramar Peninsula, Wellington, N.Z. (figs. 437, 438), serves as an example of a land-tied island. The sand isthmus connecting

* Johnson discusses the term "tombolo" and favours its retention (13, pp. 311–15).

the former island with the mainland grew out, probably, either as a cuspate foreland or a spit from the mainland at the western side, first converting the "island" into a peninsula, and then continuing on to form a bar across the mouth of a large bay, now filled, which forms the Miramar flat.

Otago Peninsula, N.Z., formerly an island isolated as a result of a submergence which drowned two valleys and the divide between their heads, forming a strait (p. 401, and figs. 388, 389), is now joined to the mainland by an isthmus which originated as a bar across the southern entrance to the strait (fig. 439).

Banks Peninsula, N.Z., is doubly tied to the mainland by bars to north and south, both of which are outgrowths from the alluvial

C. A. Cotton, photo.

FIG. 440.—The northern sand-bar joining Banks Peninsula (left) to the mainland, at low water. Note the mud-flats and channels of the enclosed lagoon (Sumner Estuary).

foreland formed by the confluent deltas of the Canterbury Plain (Haast, 50, pp. 400–1). The bar on the southern side is built of gravel (fig. 401), that on the northern side of sand (fig. 440). With the exception of the portions remaining as Lake Ellesmere and the Sumner Estuary (fig. 440), the large lagoon enclosed by the bars, the Peninsula, and the alluvial plain is now filled and converted into land.

Compound Coasts.—Coasts which display some features indicating emergence and others indicating submergence, or which combine features characteristic of a coast of either submergence

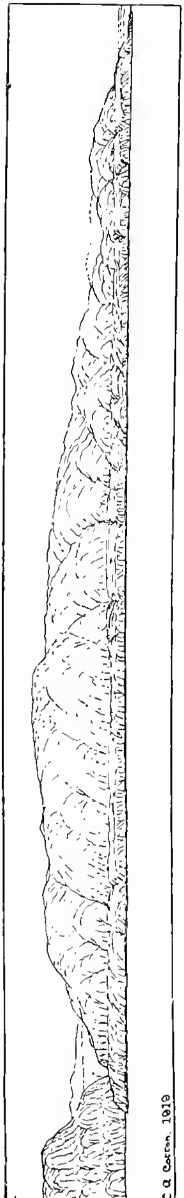


FIG. 441.—Terrace marking a former shore-line 100 ft. above lake-level, north side of Lake Taupo, N.Z.

or emergence with those of some other kind of coast — for example, a fault coast — are termed *compound* (Johnson, 13, p. 190).

The coast immediately eastward of Port Nicholson, N.Z., is compound. An uplifted coast at the contraposed stage of development is slightly depressed by the warping that submerged the neighbouring area to form Port Nicholson, so that small embayments are formed at the mouths of streams. These, however, are bridged by bay-bars (fig. 408), and the shore-line again simplified to a submature stage (fig. 430).

At Porirua also, near Wellington, N.Z., the coast is deeply embayed by subsidence, while there are remnants on the outer headlands of wave-cut platforms testifying to uplift, so that the coast is compound.

Lake-shores. — All the features of sea-coasts are reproduced on the shores of lakes, those of large lakes like the North American Great Lakes resembling those of the ocean, while the conditions in smaller lakes are more like those in landlocked harbours. Lakes in glacial troughs have shore-lines initially like those of fiords. The majority of other lakes, however, due to warping or other obstruction of drainage-channels, spread over normally eroded land-surfaces, and so their coasts are coasts of submergence. Fault coasts occur also. Lake Taupo (N.Z.), for example, is bounded mainly by fault-scarps. Coasts of emergence occur where the lake-level has been lowered by cutting-down of the outlet, or, in arid regions, by shrinkage of the lake due to evaporation.

In small lakes lowering of the lake-level generally cuts short the shore-line cycle before it has reached an advanced stage. During an interval of stationary lake-level a nip or line

of low cliffs is cut, and in front of this there is a narrow shelf, partly cut and partly built, which remains as a terrace when the lake-level falls (figs. 441, 442). Where deltas occur the terrace becomes wider, and in other parts its surface may be diversified by spits and bars. Emergent deltas are deeply trenched by the streams that built them (p. 205). Below the shore-terrace the initial form of the under-water slope may be scarcely modified by deposition. Successively lower terraces generally mark successive shore-lines during progressive lowering of lake-level; but where rapid rise of lake-level takes place in a closed basin owing to decreasing aridity shore terraces may be submerged, and they may be still recognizable as such when they re-emerge as the lake

C. A. Cotton, photo.

Fig. 442.—Lake terrace, along the base of Mount Ngongotaha, marking an ancient level of Lake Rotorua, N.Z.

shrinks again, though they will be then less sharply defined than those formed during intermittent sinking of the lake, for they will be smoothed over by the layer of fine lake-bottom sediment deposited upon them. Lake-shore terraces formed during submergence as well as during emergence of the shores occur around the margin of the large ancient lake of which Great Salt Lake, Utah, is but a shrunken remnant 1,000 ft. below the level of the highest shore-line (Gilbert, 44). In New Zealand, however, none of the former kind are known.

Ancient shore-lines are strictly horizontal (unlike river terraces), except in so far as they have been affected by warping.

APPENDIX.

READING REFERENCES.

Important Text-books and Works of Reference.

1. DAVIS, W. M., *Physical Geography*, Ginn and Co., Boston, 1898.
2. —— *Elementary Physical Geography*, Ginn and Co., Boston, 1902.
3. —— *Practical Exercises in Physical Geography*, Ginn and Co., Boston, 1908.
4. —— *Geographical Essays*, Ginn and Co., Boston, 1909.
5. —— *Die erklärende Beschreibung der Landformen*, Teubner, Leipzig, 1912.
6. GEIKIE, J., *Earth Sculpture*, Murray, London, 1904.
7. —— *Mountains, their Origin, Growth, and Decay*, Oliver and Boyd, Edinburgh, 1913.
8. GILBERT, G. K., Land Sculpture, *Report on the Geology of the Henry Mountains*, Chapter V, pp. 95–150, Washington, 1877.
9. —— The Topographic Features of Lake Shores, *U.S. Geol. Surv., 5th Ann. Rep.*, pp. 69–123, 1885.
10. GILBERT, G. K., and BRIGHAM, A. P., *An Introduction to Physical Geography*, Appleton, New York, 1911.
11. HOBBS, W. H., *Characteristics of Existing Glaciers*, Macmillan Co., New York, 1911.
12. —— *Earth Features and their Meaning*, Macmillan Co., New York, 1912.
13. JOHNSON, D. W., *Shore Processes and Shore-line Development*. Wiley, New York, 1919.
14. LAPPARENT, A. DE, *Leçons de géographie physique*, Masson, Paris, 1907.
15. MARR, J. E., *The Scientific Study of Scenery*, Methuen, London, 1900.
16. MARTONNE, E. DE, *Traité de géographie physique*, Colin, Paris, 2nd ed., 1913.
17. PENCK, A., *Morphologie der Erdoberfläche*, Engelhorn, Stuttgart, 1894.
18. PENCK, A., und BRÜCKNER, E., *Die Alpen im Eiszeitalter*, Tauchnitz, Leipzig, 1909.
19. RICHTHOFEN, F. VON, *Führer für Forschungsreisende*, Jänecke, Hannover, 1886.
20. RUSSELL, I. C., *River Development*, Murray, London, 1907.
21. SALISBURY, R. D., *Physiography*, Murray, London, 3rd ed., 1919.
22. TARR, R. S., *College Physiography*, Macmillan Co., New York, 1914.

Books and Articles, most of which are referred to in the Text, dealing with Systematic Geomorphology and with the Geomorphology of New Zealand.

23. Andrews, E. C., Some Interesting Facts concerning the Glaciation of South-western New Zealand, *Rep. 10th Meeting Austral. Assoc. Adv. Sci.*, pp. 189–205, Dunedin, 1905.
24. Aston, B. C., The Raised Beaches of Cape Turakirae, *Trans. N.Z. Inst.*, vol. 44, pp. 208–13, 1912.
25. Bartrum, J. A., High-water Rock Platforms: a Phase of Shoreline Erosion, *Trans. N.Z. Inst.*, vol. 48, pp. 132–34, 1916.
26. Campbell, M. R., Drainage Modifications and their Interpretation, *Journ. Geol.*, vol. 4, pp. 567–81, 657–78, 1896.
27. Clapp, C. H., Contraposed Shore-lines, *Journ. Geol.*, vol. 21, pp. 537–40, 1913.
28. Cockayne, L., *Report on the Dune-areas of New Zealand*, Parl. Paper C.–13, Wellington, 1911.
29. Cussen, L., Notes on the Piako and Waikato River Basins, *Trans. N.Z. Inst.*, vol. 26, pp. 398–407, 1894.
30. Daly, R. A., The Accordance of Summit Levels among Alpine Mountains, *Journ. Geol.*, vol. 13, pp. 195–25, 1905.
31. Davis, W. M., The Topographical Development of the Triassic Formation of the Connecticut Valley, *Am. Journ. Sci.*, vol. 37, pp. 423–34, 1889.
32. —— Bearing of Physiography on Uniformitarianism, *Bull. Geol. Soc. Am.*, vol. 7, pp. 8–11, 1896.
33. —— The Mountains of Southernmost Africa, *Bull. Am. Geogr. Soc.*, vol. 38, pp. 593–623, 1906.
34. —— Relation of Geography to Geology, *Bull. Geol. Soc. Am.*, vol. 23, pp. 93–124, 1912.
35. —— The Colorado Front Range: a Study in Physiographic Presentation, *Ann. Assoc. Am. Geogr.*, vol. 1, pp. 21–83, 1912.
36. —— Nomenclature of Surface Forms on Faulted Structures, *Bull. Geol. Soc. Am.*, vol. 24, pp. 187–216, 1913.
37. —— Meandering Valleys and Underfit Rivers, *Ann. Assoc. Am. Geogr.*, vol. 3, pp. 3–28, 1914.
38. —— The Principles of Geographical Description, *Ann. Assoc. Am. Geogr.*, vol. 5, pp. 61–105, 1915.
39. —— A Shaler Memorial Study of Coral Reefs, *Am. Journ. Sci.*, vol. 40, pp. 223–71, 1915.
40. Doyne, W. T., *Second Report upon the River Waimakariri* . . . Christchurch, 1865.
41. Drew, F., Alluvial and Lacustrine Deposits and Glacial Records of the Upper Indus Basin, *Quart. Journ. Geol. Soc.*, vol. 29, pp. 441–71, 1873.

42. Fenneman, N. M., Development of the Profile of Equilibrium of the Subaqueous Shore Terrace, *Journ. Geol.*, vol. 10, pp. 1–32, 1902.
43. —— Lakes of South-eastern Wisconsin, *Wis. Geol. and Nat. Hist. Surv. Bull. No. 8*, 1902.
44. Gilbert, G. K., Lake Bonneville, *U.S. Geol. Surv. Monogr. 1*, 1890.
45. —— Glaciers and Glaciation (Harriman Alaska Expedition), *Alaska*, vol. 3, New York, 1903 (also Smithsonian Institution, Washington, 1910).
46. —— Systematic Asymmetry of the Crest Lines in the High Sierra of California, *Journ. Geol.*, vol. 12, pp. 579–88, 1904.
47. —— The Lowering of Hilltops, *Journ. Geol.*, vol. 17, pp. 344–50, 1909.
48. Gulliver, F. P., Shore-line Topography, *Proc. Am. Acad. Arts and Sci.*, vol. 34, pp. 150–258, 1899.
49. Haast, J., *Report on the Formation of the Canterbury Plains*, Christchurch, 1864.
50. Haast, J. von, *Geology of the Provinces of Canterbury and Westland, New Zealand*, Christchurch, 1879.
51. Hochstetter, F. von, Geologie von Neu-Seeland, *Reise . . . Novara*, 1 Band, 1 Abt., Wien, 1864.
52. —— *New Zealand*, Cotta. Stuttgart, 1867.
53. Johnson, W. D., The Profile of Maturity in Alpine Glacial Erosion, *Journ. Geol.*, vol. 12, pp. 569–78, 1904.
54. Jutson, J. T., Erosion and the Resulting Land Forms in Sub-arid Western Australia, *Geogr. Journ.*, vol. 50, pp. 418–37, 1917.
55. Lawson, A. C., Epigene Profiles of the Desert, *Univ. Calif. Publ. Bull. Dept. Geol.*, vol. 9, pp. 23–48, 1915.
56. Lyell, C., *Principles of Geology*, vol. 2, 10th ed., 1868.
57. McKay, A., *Report on the Recent Seismic Disturbances . . .* Wellington, 1902.
58. Marshall, P., The Geology of Dunedin, New Zealand, *Quart. Journ. Geol. Soc.*, vol. 62. pp. 381–424, 1906.
59. —— *The Geography of New Zealand*, Whitcombe and Tombs, Christchurch.
60. —— *Geology of New Zealand*, Government Printer, Wellington, 1912.
61. Martonne, E. de, L'Érosion glaciaire et la formation des vallées alpines, *Ann. de Géog.*, vol. 19, pp. 289–317, vol. 20, pp. 1–29, 1910–11.
62. Matthes, F. E., Glacial Sculpture of the Bighorn Mountains, *U.S. Geol. Surv., 21st Ann. Rep.*, Part 2, 167–90, 1900.
63. Morgan, P. G., Notes on the Geology of the Patea District, *Trans. N.Z. Inst.*, vol. 53, pp. 58–64, 1921.
64. New Zealand Geological Survey, *Bulletins*, 1906–21.

65. Park, J., *The Geology of New Zealand*, Whitcombe and Tombs, Christchurch, 1910.
66. Penck, A., Die Übertiefung der Alpenthäler, *Verhandl. d. VII internat. Geogr.-Kongr.*, Berlin, 1900.
67. —— Glacial Features in the Surface of the Alps, *Journ. Geol.*, vol. 13, pp. 1–19, 1905.
68. —— The Origin of the Alps, *Bull. Am. Geogr. Soc.*, vol. 41, pp. 65–71, 1909.
69. Playfair, J., Illustrations of the Huttonian Theory of the Earth, Creech, Edinburgh, 1802.
70. Ramsay, A. C., On the Glacial Origin of Certain Lakes in Switzerland, *Quart. Journ. Geol. Soc.*, vol. 18, pp. 186–204, 1862.
71. Richter, E., Geomorphologische Untersuchungen in den Hochalpen, *Peterm. Mitteil. Erganzungsheft 132*, 1900.
72. Smith, S. Percy, *The Eruption of Tarawera: a Report to the Surveyor-General*, Wellington, 1886.
73. Speight, R., Some Aspects of the Terrace-development in the Valleys of the Canterbury Rivers, *Trans. N.Z. Inst.*, vol. 40, pp. 16–43, 1908.
73a. —— "Geological History," in L. Cockayne's *Report of a Botanical Survey of the Tongariro National Park*, Parl. Paper C.–11, pp. 7–12, Wellington, 1908.
74. —— The Mount Arrowsmith District: a Study in Physiography and Plant Ecology—Part I, Physiography, *Trans. N.Z. Inst.*, vol. 43, pp. 317–42, 1911.
75. —— The Geology of Banks Peninsula, *Trans. N.Z. Inst.*, vol. 49, pp. 365–94, 1917.
76. —— Structural and Glacial Features of the Hurunui Valley, *Trans. N.Z. Inst.*, vol. 50, pp. 93–105, 1918.
77. —— The Modification of Spur-ends by Glaciation, *Trans. N.Z. Inst.*, vol. 53, pp. 47–53, 1921.
78. Thomson, J., On the Origin of Windings of Rivers . . . *Proc. Roy. Soc.*, vol. 25, pp. 5–8, 1876.
79. Thomson, J. Allan, Coal Prospects of the Waimate District, South Canterbury, *Eighth Ann. Rep.* [*N.Z.*] *Geol. Surv.*, Parl. Paper C.–2, pp. 158–62, Wellington, 1914.
80. —— Mineral Prospects of the Maharahara District, Hawke's Bay, *ibid.*, pp. 162–70, 1914.
81. Whitaker, W., On Subaerial Denudation, *Geol. Mag.*, vol. 4, p. 474, 1867.

Papers by the Author.

82. Cotton, C. A., Notes on Wellington Physiography, *Trans. N.Z. Inst.*, vol. 44, pp. 245–65, 1912.
83. —— Recent and Sub-recent Movements of Uplift and of Subsidence near Wellington, New Zealand, *Scot. Geogr. Mag.*, vol. 28, pp. 306–12, 1912.

84. Cotton, C. A., The Physiography of the Middle Clarence Valley, New Zealand, *Geogr. Journ.*, vol. 42, pp. 225–46, 1913.
85. —— The Tuamarina Valley: a Note on the Quaternary History of the Marlborough Sounds District, *Trans. N.Z. Inst.*, vol. 45, pp. 316–22, 1913.
86. —— Preliminary Note on the Uplifted Coast of Marlborough, *Trans. N.Z. Inst.*, vol. 46, pp. 286–94, 1914.
87. —— Supplementary Notes on Wellington Physiography, *Trans. N.Z. Inst.*, vol. 46, pp. 294–98, 1914.
88. —— Fault Coasts in New Zealand, *Geogr. Review*, vol. 1, pp. 20–47, 1916.
89. —— The Structure and Later Geological History of New Zealand, *Geol. Mag.*, decade 6, vol. 3, pp. 243–49, 314–20, 1916.
90. —— Block Mountains and a "Fossil" Denudation Plain in Northern Nelson, *Trans. N.Z. Inst.*, vol. 48, pp. 59–75, 1916.
91. —— Block Mountains in New Zealand, *Am. Journ. Sci.*, vol. 44, pp. 249–93, 1917.
92. —— The Fossil Plains of North Otago, *Trans. N.Z. Inst.*, vol. 49, pp. 429–32, 1917.
93. —— New Zealand's Niagara, *N.Z. Journ. Sci. and Tech.*, vol. 1, pp. 9–11, 1918.
94. —— The Geomorphology of the Coastal District of South-western Wellington, *Trans. N.Z. Inst.*, vol. 50, pp. 212–22, 1918.
95. —— River Terraces in New Zealand, *N.Z. Journ. Sci. and Tech.*, vol. 1, pp. 145–52, 1918.
96. —— Mountains, *N.Z. Journ. Sci. and Tech.*, vol. 1, pp. 280–85, 1918.
97. —— The Outline of New Zealand, *Geogr. Review*, vol. 6, pp. 320–40, 1918.
98. —— Rough Ridge, Otago, and its Splintered Fault-scarp, *Trans. N.Z. Inst.*, vol. 51, pp. 282–85, 1919.
99. —— For how long will Wellington escape Destruction by Earthquake? *N.Z. Journ. Sci. and Tech.*, vol. 3, pp. 229–31, 1921.
100. —— The Warped Land-surface on the South-eastern Side of the Port Nicholson Depression, Wellington, N.Z., *Trans. N.Z. Inst.*, vol. 53, pp. 131–43, 1921.
101. —— Advances in Physiography in New Zealand in the Last Ten Years, *Rep. 15th Meeting Austral. Assoc. Adv. Sci.*, pp. 335–42, Melbourne, 1921.

INDEX.

By Authority: W. A. G. Skinner, Government Printer, Wellington.
[1,000/7/21—11274